From:	Yamato, Alison
To:	Kurt Repanshek
Cc:	Pete Webster
Subject:	FOIA NPS-2019-1151
Date:	Thursday, December 12, 2019 3:33:58 PM
Attachments:	19-1151_Repanshek_Final.docx

Mr. Rapanshek,

Attached you should find our final response to your request. I have to send the responsive documents separately from our file transfer site due to the size of them. I greatly appreciate your patience!! Thanks!

-Alison

--

"Do what you can, with what you have, where you are."
-Theodore Roosevelt

Alison Yamato
Government Information Specialist - NPS Regional FOIA Officer & Coordinator
Servicing DOI Regions 6,7, & 8
12795 W Alameda Pkwy
Lakewood, CO 80228
303.969.2242 (O)
303.243.4096 (C)

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United States Department of the Interior

NATIONAL PARK SERVICE
INTERIOR REGIONS 6, 7 & 8
12795 W. Alameda Parkway
Lakewood, CO 80228

IN REPLY REFER TO:
NPS-2019-01598 (BIBE)

December 11, 2019
Electronic Transmission – No Hard Copy to Follow

Kurt Repanshek
PO Box 980452
Park City, UT 84098
kurt@nationalparkstraveler.org

Dear Mr. Repanshek:

Reference: Glacier National Park (GLAC)

Subject: Freedom of Information Act Request NPS-2019-01151

The control number for your request is provided above. Please cite this number in any future communications with our office regarding your request. This letter is in response to your Freedom of Information Act (FOIA) request dated, June 14, 2019, in which you requested:

> Documents related to…correspondence, emails, etc. regarding the decision to remove any signs indicating that glaciers "will be gone by 2020..."

Upon further review, your request is granted in part and denied in part. We are providing you 5 file(s) totaling 940 pages of responsive records. However, portions of 45 pages are being withheld under Exemption 6.

> Exemption 6 allows an agency to withhold "personnel and medical files and similar files the disclosure of which would constitute a clearly unwarranted invasion of personal privacy." 5 U.S.C. § 552(b)(6). We are withholding [NOTE: Estimate the volume of any records or information withheld, for example We are withholding approximately 33 pages in part under Exemption 6.
>
> The phrase "similar files" covers any agency records containing information about a particular individual that can be identified as applying to that individual. To determine whether releasing records containing information about a particular individual would constitute a clearly unwarranted invasion of personal privacy, we are required to balance the privacy interest that would be affected by disclosure against any public interest in the information.
>
> Under the FOIA, the only relevant public interest to consider under the exemption is the extent to which the information sought would shed light on an agency's performance of

its statutory duties or otherwise let citizens 'know what their government is up to. The burden is on the requester to establish that disclosure would serve the public interest. When the privacy interest at stake and the public interest in disclosure have been determined, the two competing interests must be weighed against one another to determine which is the greater result of disclosure: the harm to personal privacy or the benefit to the public. The purposes for which the request for information is made do not impact this balancing test, as a release of information requested under the FOIA constitutes a release to the general public.

The information that has been withheld under Exemption 6 consists of personal information, such as personal physical and electronic addresses and phone numbers and we have determined that the individuals to whom this information pertains have a substantial privacy interest in withholding it. Additionally, {you have not provided information that explains a relevant public interest under the FOIA in the disclosure of this personal information and} we have determined that the disclosure of this information would shed little or no light on the performance of the agency's statutory duties. Because the harm to personal privacy is greater than whatever public interest may be served by disclosure, release of the information would constitute a clearly unwarranted invasion of the privacy of these individuals and we are withholding it under Exemption 6.

Alison Yamato, National Park Service, Intermountain Region FOIA Coordinator is responsible for this response.

Because the National Park Service creates and maintains law enforcement records, we are required by the Department of Justice to provide the following information, even though it may or may not apply to your specific request. Congress excluded three discrete categories of law enforcement and national security records from the requirements of the FOIA. See 5 U.S.C. 552(c) (2006 & Supp. IV 2010). This response is limited to those records that are subject to the requirements of the FOIA. This is a standard notification that we are required to give all our requesters and should not be taken as an indication that excluded records do, or do not, exist.

You may appeal this response to the Department's FOIA/Privacy Act Appeals Officer. If you choose to appeal, the FOIA/Privacy Act Appeals Officer must receive your FOIA appeal no later than 90 workdays from the date of this letter. Appeals arriving or delivered after 5 p.m. Eastern Time, Monday through Friday, will be deemed received on the next workday.

Your appeal must be made in writing. You may submit your appeal and accompanying materials to the FOIA/Privacy Act Appeals Officer by mail, courier service, fax, or email. All communications concerning your appeal should be clearly marked with the words: "FREEDOM OF INFORMATION APPEAL." You must include an explanation of why you believe the NPS' response is in error. You must also include with your appeal copies of all correspondence between you and the NPS concerning your FOIA request, including your original FOIA request and NPS' response. Failure to include with your appeal all correspondence between you and the NPS will result in the Department's rejection of your appeal, unless the FOIA/Privacy Act Appeals Officer determines (in the FOIA/Privacy Act Appeals Officer's sole discretion) that good cause exists to accept the defective appeal.

Please include your name and daytime telephone number (or the name and telephone number of an appropriate contact), email address and fax number (if available) in case the FOIA/Privacy Act Appeals Officer needs additional information or clarification of your appeal.

DOI FOIA/Privacy Act Appeals Office Contact Information:

Department of the Interior
Office of the Solicitor
1849 C Street, N.W.
MS-6556 MIB
Washington, DC 20240
Attn: FOIA/Privacy Act Appeals Office
Telephone: (202) 208-5339
Fax: (202) 208-6677
Email: FOIA.Appeals@sol.doi.gov

The 2007 FOIA amendments created the Office of Government Information Services (OGIS) to offer mediation services to resolve disputes between FOIA requesters and Federal agencies as a non-exclusive alternative to litigation. Using OGIS services does not affect your right to pursue litigation. You may contact OGIS in any of the following ways:

Office of Government Information Services
National Archives and Records Administration
8601 Adelphi Road - OGIS
College Park, MD 20740-6001
E-mail: ogis@nara.gov
Web: https://ogis.archives.gov
Telephone: 202-741-5770
Fax: 202-741-5769
Toll-free: 1-877-684-6448

Please note that using OGIS services does not affect the timing of filing an appeal with the Department's FOIA & Privacy Act Appeals Officer. You also may seek dispute resolution services from our FOIA Public Liaison,

Ms. Charis Wilson, Ph,D., CRM
NPS FOIA Officer
12795 W. Alameda Parkway
PO Box 25287
Denver, CO 80225-0287
303-969-2959
Fax: 303-969-2557
1-855-NPS-FOIA

Should you have any further questions regarding this request, please feel free to contact me. I can be reached at the address above or by phone at 303.969.2242. My e-mail address is Alison_Yamato@nps.gov.

Sincerely,

/s/

Alison Yamato
NPS IMR FOIA Officer

Sincerely,

/s/

Alison Yamato
NPS Regional FOIA Officer

Conversation Contents

If visitors ask when the glaciers will be gone:

Attachments:

/1. If visitors ask when the glaciers will be gone:/1.1 STMARY-VC-EXHIBIT-1-OLD.png
/1. If visitors ask when the glaciers will be gone:/1.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/1.3 STMARY-VC-EXHIBIT-2-OLD.png
/1. If visitors ask when the glaciers will be gone:/1.4 STMARY-VC-EXHIBIT-2-UPDATED.png

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Fri Jun 14 2019 11:49:40 GMT-0600 (MDT)
To:	Marc Neidig <marc_neidig@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>
CC:	William Hayden <bill_hayden@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>
Subject:	If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

If visitors ask when the glaciers will be gone:
Data show that in 1966, the park had 35 named glaciers large enough to be considered active. By 2015, only 26 named glaciers remained in that category. The average area reduction was 39 percent, though some lost as much as 85 percent. This trend of glacier retreat is expected to continue as temperatures rise. Some small remnant ice may persist late into the 21st century or even beyond, depending on future rates of climate change.

These updated webpages are your best secondary sources for information on the park's glaciers:

- https://www.nps.gov/glac/learn/nature/melting-glaciers.htm
- https://www.nps.gov/glac/learn/nature/how-to-see-a-glacier.htm
- https://www.nps.gov/glac/learn/nature/glacial-geology.htm

Background on previously used prediction dates:
A USGS geospatial model published in a 2003 paper predicted that Blackfoot and Jackson would be gone by 2030. Because these are two of the larger glaciers in the park (2nd and 6th respectively in 1966), it was extrapolated that if they were gone, the rest of the glaciers in the park would be gone too. The predicted date of 2030 was put on several exhibits throughout the park, including in the Apgar and St. Mary Visitor Center plazas.

Further research in the late 2000s (page 80) revealed that Jackson and Blackfoot glaciers were melting even faster than the rate predicted in the 2003 geospatial model. So fast, in fact, that if the rate continued they would be gone by 2020. It was then extrapolated that if Blackfoot and Jackson were gone by 2020, the rest of the glaciers in the park would be gone too. The 2020 date was then put on two exhibits outside the Logan Pass Visitor Center and on two exhibits inside the St. Mary Visitor Center (see below).

In May, 2019 the St. Mary Visitor Center exhibits were updated to reflect the analyses, data, and insights that have emerged since 2010. This latest research shows shrinking of all the park's glaciers but in ways far more complicated, and interesting, than expressed in the early 2000s. In the three places that used the 2020 date, the exhibits now say: *"Future Generations;" "When they will completely disappear, however, depends on how and when we act;"* and *"Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking."* (See images below.)

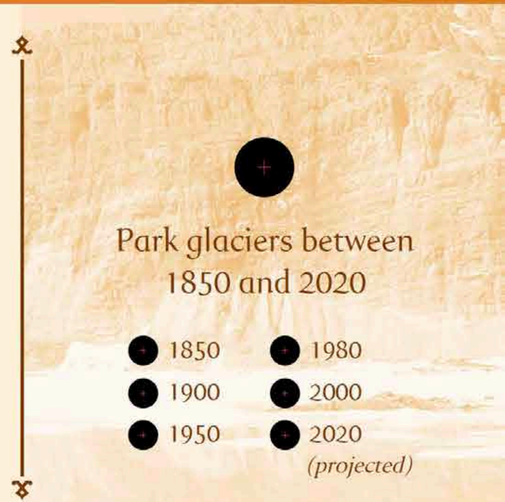
There are plans to update all the other exhibits (at the Logan Pass, Apgar, and St. Mary visitor centers) that use the 2020 and 2030 dates as time and funding allows.

STMARY-VC-EXHIBIT-1-OLD.png
STMARY-VC-EXHIBIT-1-UPDATED.png
STMARY-VC-EXHIBIT-2-OLD.png
STMARY-VC-EXHIBIT-2-UPDATED.png

GOODBYE TO THE GLACIERS

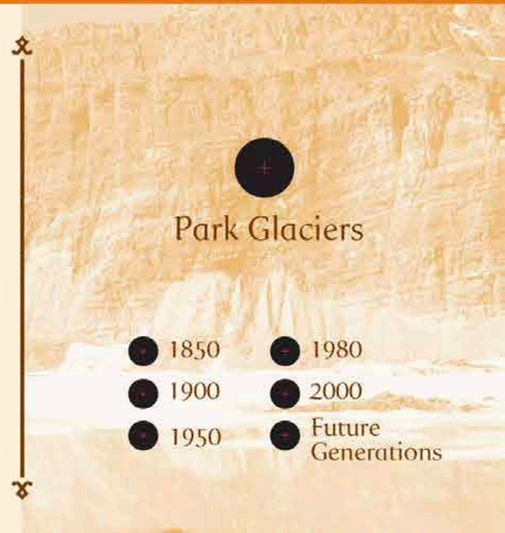
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. They are now rapidly shrinking due to human-caused climate change. Computer models indicate the glaciers will all be gone by the year 2020.

Glacier National Park was named for the sculpting actions of the Pleistocene glaciers that covered this landscape 12,000 to 130,000 years ago.



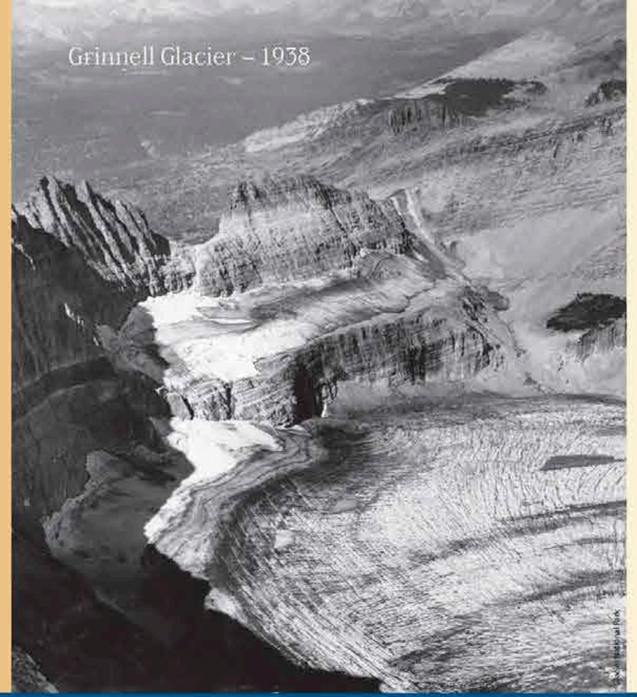
GOODBYE TO THE GLACIERS

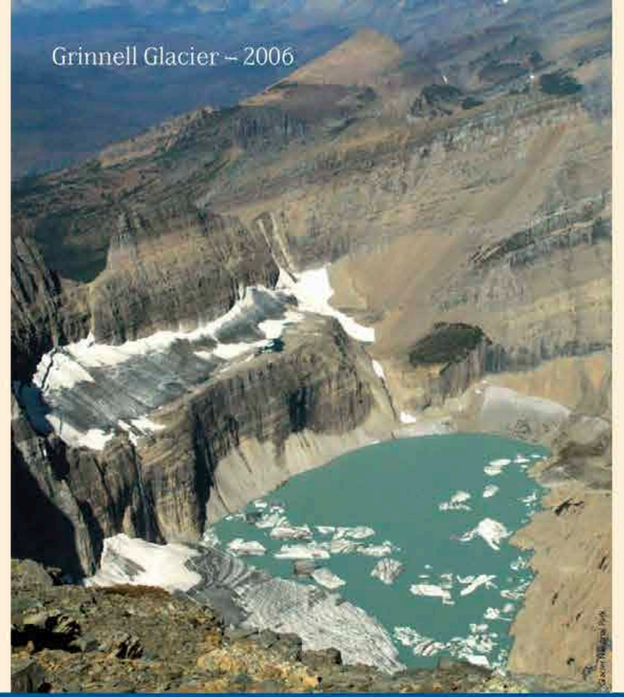
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum size and number around 1850, at the end of the Little Ice Age. Currently, they are rapidly shrinking due to human-accelerated climate change. When they will completely disappear, however, depends on how and when we act.



Glaciers are moving masses of ice. The glaciers that shaped the park were massive. During the pleistocene—12,000–130,000 years ago—the glaciers covering this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

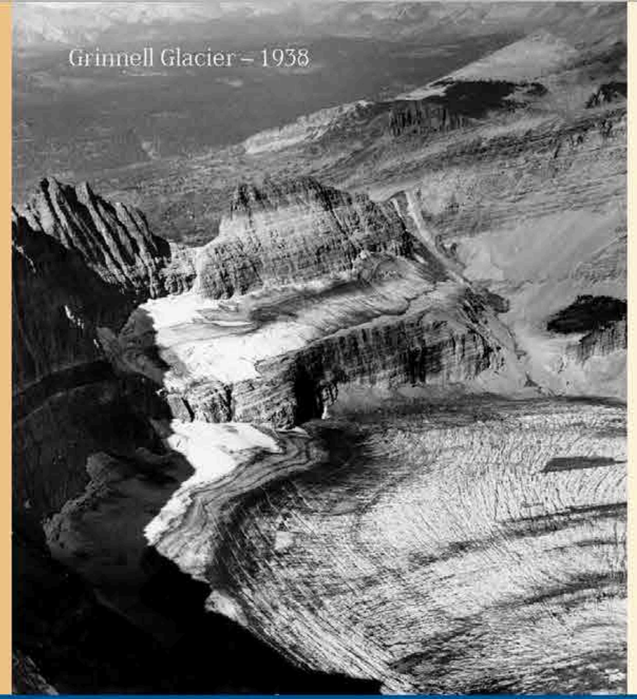
In 1850 there were 150 glaciers in the park; in 2010 the number decreased to 25. Current climate models suggest that all of the glaciers in Glacier National Park will be gone by 2020.

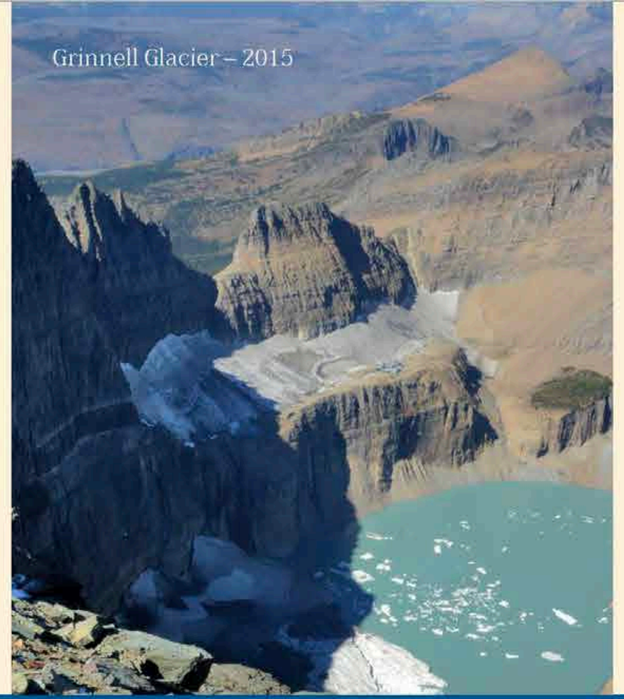
Grinnell Glacier, located high in the Many Glacier valley, has significantly retreated in recent decades.

GLACIERS ON THE MOVE

Glaciers are moving masses of ice. During the Pleistocene—12,000–130,000 years ago—the massive glaciers shaping this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

In 1850 there were about 150 glaciers in the park. In 2015, only 26 named glaciers remained in the park.

Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking. Grinnell Glacier, located high in the Many Glacier Valley, has lost 45% of its area in recent decades.

GLACIERS ON THE MOVE

Conversation Contents

Fwd: [EXTERNAL] Glacier's glaciers

Attachments:

/1. Fwd: [EXTERNAL] Glacier's glaciers/1.1 NPT color logo_TM 2 300.png

"Barnum, Jeremy" <jeremy_barnum@nps.gov>

From:	"Barnum, Jeremy" <jeremy_barnum@nps.gov>
Sent:	Mon Jun 17 2019 15:55:54 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, Kathy Kupper <kathy_kupper@nps.gov>
Subject:	Fwd: [EXTERNAL] Glacier's glaciers
Attachments:	NPT color logo_TM 2 300.png

Hi Lauren,

See Kurt's email below. Are you okay with us responding with the following?

"The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.

The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling."

Jeremy K. Barnum
Acting Assistant Director, Communications
Chief Spokesperson/Chief of Public Affairs
National Park Service
Office: (202) 513-7262
Mobile: (202) 617-7973
Facebook Twitter Instagram YouTube

---------- Forwarded message ---------
From: **Kurt Repanshek** <kurt@nationalparkstraveler.org>
Date: Mon, Jun 17, 2019 at 2:33 PM
Subject: [EXTERNAL] Glacier's glaciers
To: Kupper, Kathy <Kathy_Kupper@nps.gov>
Cc: Jeremy Barnum <jeremy_barnum@nps.gov>

Kathy,

There has been some hubbub over removal of signs at Glacier National Park saying the park's glaciers might be gone by 2020. I've tried to ignore it, but folks keep asking.

I asked Jeff Mow about it, and he referred me to Dan Fagre at USGS, who said he was told not to talk to me, but that my questions should go to you.

Can you explain why the signs were taken down, and can you explain why Dan is not allowed to speak to me?

Best,

Kurt

Kurt Repanshek
Founder, Editor-in-Chief
kurt@nationalparkstraveler.org

National Parks Traveler is the nation's No. 1 editorially independent website dedicated to coverage of national parks. With 1.6 million annual visitors, Traveler has been featured in USA Today, Peter Greenberg Worldwide Radio, Los Angeles Times, San Jose Mercury News, The Charlotte Observer, aol.travel and more.

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Jeremy Barnum <jeremy_barnum@nps.gov>

From:	Jeremy Barnum <jeremy_barnum@nps.gov>
Sent:	Mon Jun 17 2019 18:12:50 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, Kathy Kupper <kathy_kupper@nps.gov>

Subject: Re: [EXTERNAL] Glacier's glaciers

I'll go ahead and provide this response..... Jeremy Barnum National Park Service > On Jun 17, 2019, at 5:55 PM, Barnum, Jeremy <jeremy_barnum@nps.gov> wrote: > > "The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem. > > The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling."

Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Mon Jun 17 2019 18:50:18 GMT-0600 (MDT)
To:	Jeremy Barnum <jeremy_barnum@nps.gov>
CC:	Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, Kathy Kupper <kathy_kupper@nps.gov>
Subject:	Re: [EXTERNAL] Glacier's glaciers

This looks good. When I'm back tomorrow at my computer I'll forward you what we already sent him. He asked us the same question. Sent from my iPhone > On Jun 17, 2019, at 6:12 PM, Jeremy Barnum <jeremy_barnum@nps.gov> wrote: > > I'll go ahead and provide this response..... > > Jeremy Barnum > National Park Service > >> On Jun 17, 2019, at 5:55 PM, Barnum, Jeremy <jeremy_barnum@nps.gov> wrote: >> >> "The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem. >> >> The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling."

Conversation Contents

If visitors ask when the glaciers will be gone: - Invitation to edit

"Daniel Lombardi (via Google Docs)" <drive-shares-noreply@google.com>

From:	"Daniel Lombardi (via Google Docs)" <drive-shares-noreply@google.com>
Sent:	Thu Jun 13 2019 11:19:15 GMT-0600 (MDT)
To:	<lauren_alley@nps.gov>
Subject:	If visitors ask when the glaciers will be gone: - Invitation to edit

daniel_lombardi@nps.gov has invited you to **edit** the following document:

If visitors ask when the glaciers will be gone:

Open in Docs

Google Docs: Create and edit documents online.

Google LLC, 1600 Amphitheatre Parkway, Mountain View, CA 94043, USA

You have received this email because someone shared a document with you from Google Docs.

Conversation Contents

[EXTERNAL] Glacier Signs

Attachments:

/3. [EXTERNAL] Glacier Signs/1.1 FlatheadBeacon.png
/3. [EXTERNAL] Glacier Signs/1.2 EditorsClub.png
/3. [EXTERNAL] Glacier Signs/2.1 FlatheadBeacon.png
/3. [EXTERNAL] Glacier Signs/2.2 EditorsClub.png

Tristan Scott <tscott@flatheadbeacon.com>

From:	Tristan Scott <tscott@flatheadbeacon.com>
Sent:	Wed Jun 12 2019 13:37:08 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
Subject:	[EXTERNAL] Glacier Signs
Attachments:	FlatheadBeacon.png EditorsClub.png

Hi Lauren,

I'm getting a bunch of calls from people wondering why we're not reporting on "Glacier removing its Gone by 2020 signs" and I don't have an answer, other than I don't know if that's happening and I've never seen those signs. Could you illuminate me when you get a chance? No reputable news organizations have reported this. Thanks for looking into it.

Best,
Tristan

Tristan Scott, Senior Writer | tscott@flatheadbeacon.com
CELL: 406.531.9745 OFFICE: 406.257.9220
17 Main Street, Kalispell, MT 59901 | FLATHEADBEACON.COM

"Alley, Lauren" <lauren_alley@nps.gov>

From:	"Alley, Lauren" <lauren_alley@nps.gov>
Sent:	Wed Jun 12 2019 14:05:10 GMT-0600 (MDT)
To:	Tristan Scott <tscott@flatheadbeacon.com>
Subject:	Re: [EXTERNAL] Glacier Signs
Attachments:	FlatheadBeacon.png EditorsClub.png

Tristan,

Thanks for reaching out about this. Please also see this link for more language.

If you really want to get into it, you can get in touch with USGS about the glacier margins research released in 2017.

Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.

The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.

USGS regularly publicizes their research efforts. The National Park Service does not typically issue press releases for new interpretive displays or park signage.

The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

On Wed, Jun 12, 2019 at 1:37 PM Tristan Scott <tscott@flatheadbeacon.com> wrote:

> Hi Lauren,
>
> I'm getting a bunch of calls from people wondering why we're not reporting on "Glacier removing its Gone by 2020 signs" and I don't have an answer, other than I don't know if that's happening and I've never seen those signs. Could you illuminate me when you get a chance? No reputable news organizations have reported this. Thanks for looking into it.
>
> Best,
> Tristan
>
> Tristan Scott, Senior Writer | tscott@flatheadbeacon.com
> CELL: 406.531.9745 OFFICE: 406.257.9220
> 17 Main Street, Kalispell, MT 59901 | FLATHEADBEACON.COM

Conversation Contents

Fwd: Information Sources on the Park's Glaciers

Attachments:

/4. Fwd: Information Sources on the Park's Glaciers/1.1 CLIMATE CHANGE COMMS ecoAmerica-CRED-2014-Connecting-on-Climate.pdf

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed Jun 12 2019 09:46:55 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
Subject:	Fwd: Information Sources on the Park's Glaciers
Attachments:	CLIMATE CHANGE COMMS ecoAmerica-CRED-2014-Connecting-on-Climate.pdf

Here's resources we have for people to learn more about impacts seen in the park.

Images and videos of the Howe Ridge Fire https://www.flickr.com/photos/glaciernps/albums/72157694303392450

One of those images was used as the cover photo/story of this national report: https://nca2018.globalchange.gov/downloads/NCA4_Report-in-Brief.pdf

Here's pictures of many of the park's exhibits: https://www.flickr.com/photos/glaciernps/albums/72157648750913499

---------- Forwarded message ---------
From: **Lombardi, Daniel** <daniel_lombardi@nps.gov>
Date: Mon, Jun 3, 2019 at 1:49 PM
Subject: Information Sources on the Park's Glaciers
To: Sine, Diane <diane_sine@nps.gov>

Hey Diane,

Here's a bunch of academic papers that the USGS folks have given to me over the past year while trying to answer my questions about the park's melting ice. I'm sure you'll be fairly familiar with much of it but some of it might be handy.

You might notices that a some of the attached papers, to some extent, contradict the notion that, even with substantial and immediate carbon emissions reductions, there is little hope of saving the park's glaciers. (Brown 2010, Clarke 2015, and Huss 2017 all show ice persisting under some reduced carbon regime for most of the century, implying, to my limited understanding, that might be some time to save the glaciers.) It is only the supplemental figures for Bosson 2019 that show the park's ice disappearing so soon that there is clearly no time to do anything about it.

If you haven't seen it yet, I updated a few sections this winter that you might find useful. If you spot any mistakes or areas that need improvement, or if you have ideas for other webpages, please let me know.

https://www.nps.gov/glac/learn/nature/glaciersoverview.htm
https://www.nps.gov/glac/learn/nature/melting-glaciers.htm
https://www.nps.gov/glac/learn/nature/how-to-see-a-glacier.htm
https://www.nps.gov/glac/learn/nature/glacial-geology.htm
https://www.nps.gov/glac/learn/nature/climate-change.htm
https://www.nps.gov/glac/getinvolved/sustainability.htm
https://www.nps.gov/glac/getinvolved/how-to-reduce-your-carbon-footprint.htm

Lastly, I'm also going to share a communication tips sheet and powerpoint that I wrote up this winter based on the suggestions of the attached Columbia Center for Environmental Decisions and EcoAmerica booklet.

- Bosson_et_al-2019-Earth's_Future.pdf
- Brown_2010_GPC.pdf
- Clarke_2015_NatureGeoscience.pdf
- glacier anthropogenic attribution studies.pdf
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CONNECTING ON CLIMATE:

A Guide to Effective Climate Change Communication

ecoAmerica
start with people

Center for Research on Environmental Decisions
EARTH INSTITUTE | COLUMBIA UNIVERSITY

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About the Center for Research on Environmental Decisions

CRED is an interdisciplinary center that studies individual and group decision making under climate uncertainty and decision making in the face of environmental risk. CRED's objectives address the human responses to climate change and climate variability as well as improved communication and increased use of scientific information on climate variability and change. Located at Columbia University, CRED is affiliated with the Earth Institute. For more information visit ***cred.columbia.edu***.

About ecoAmerica

ecoAmerica grows the base of popular support for climate solutions in America with research-driven marketing, partnerships, and national programs that connect with Americans' core values to bring about and support change in personal and civic voices and behaviors. For more information, visit ***ecoAmerica.org***.

We welcome feedback on this guide. Please send emails to ***connectingonclimate@gmail.com***.

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FOREWORD: A CONTEXT FOR CLIMATE CHANGE COMMUNICATION

For most of the past two centuries climate change has been discussed as a scientific phenomenon. The creation of fossil fuels, the chemistry of combustion, and the resulting changes in the atmosphere and planetary temperatures could be explained in no other way.

Then, in the 1980s, from his post at NASA's Goddard Institute for Space Studies, Dr. Jim Hansen began to describe the implications of the planet's rising temperatures. His testimony before Congress in 1988, coupled with Bill McKibben's book *The End of Nature* in 1989, brought the issue to the public's eye.[1] Hansen and McKibben framed global warming in dramatic terms—rising sea levels, melting Arctic sea ice, and extreme flood and droughts—and ushered in an era of framing climate change as planetary destruction.

This pairing of scientific analysis and potentially catastrophic implications moved America and other nations toward action. The formation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and passage of the United States Global Change Research Act of 1990 led to the UN Framework on Climate Change process, which yielded the Kyoto Protocol in 1997 and legally binding obligations for nations to reduce their greenhouse gas emissions.

In the midst of these major changes, some businesses came to view climate change as a threat to profits. In the 1990s, certain groups began organizing and funding activities to discredit climate science and to stop progress on climate solutions. This ushered in an era of opposition messaging and political polarization on climate change.[2]

The first decade of the new millennium saw an ongoing battle between these two forces. On one side, the Bush administration opposed action on climate change, seeing it as a trade-off with economic growth. On the other side, in 2006, former vice president Al Gore surfaced with the film and the book *An Inconvenient Truth*, which attempted to galvanize further large-scale action on climate change.

In 2009, the incoming Obama administration shifted away from Gore in its approach to communicating climate change. Research and experience suggested that fear-based arguments had run their course as effective tools for inspiring action. So Obama pivoted his focus toward the

co-benefits of climate action, prompting a focus on the economic, social, and health benefits of climate solutions.[3]

On one hand, it seems that none of these communication frames has been decisive. Yet the opposite perspective is in fact more accurate. Each of these arguments has influenced the political, economic, cultural, and psychological factors that mold today's climate debate. It has been a pitched battle to a draw, which is a loss for humanity and the planet.

Then, beginning with no specific event or time, the impacts of a warming planet began emerging. From California to Pakistan, from New Orleans to Bangkok, unprecedented and costly droughts, floods, and extreme weather emerged across the planet. A new era of climate communication emerged—the era of climate impacts.

So where do we go from here? The reality of climate change is upon us. Whether directly or latently, people are becoming more concerned about the issue. They seek guidance on what climate change is, what it means for their loved ones, and what they can do about it in a complex communication climate. Moreover, hundreds of people and organizations seek to refine their communication approaches to help further the case for meaningful action on the issue.

The Center for Research on Environmental Decisions (CRED) at The Earth Institute, Columbia University, and ecoAmerica, a nonprofit that works to build public support for climate solutions, have been leaders in climate communication research. With this guide, we synthesize what others and we have learned about climate change communication over the years into a single useful tool. It is our hope that leaders and communicators will put the insights in this guide into practice, designing and sharing ever more effective communication and practices to motivate an era of climate engagement that pushes America—and the planet—to a tipping point for climate solutions.

USING THIS GUIDE TO UNLOCK SUCCESS IN CLIMATE CHANGE COMMUNICATION

Climate change is not a new issue, but the need for meaningful and sustainable solutions is more urgent than ever. Climate communicators and mainstream leaders are still grappling with how to help Americans find meaningful, actionable paths forward and overcome the social, political, psychological, and emotional barriers that have hindered progress on climate solutions.

To connect with audiences and unlock success in climate change communication, communicators need to shift their approach. Communicators need to go beyond simply providing people with the facts about climate change. They need to connect with people's values and worldviews and put solutions at the forefront to make climate change personally relevant to Americans and those they love.

Getting climate communication right is becoming increasingly important for at least three reasons. First, the issue and timing are both critical. The impacts of climate change are accelerating, and delaying meaningful action to reduce carbon emissions increases the probability of harmful impacts. Second, climate change remains abstract, remote, and distant for many Americans, most of whom are focused on their more immediate needs.[4] Third, influential political and economic actors are organizing solidly against actions to reduce the carbon emissions driving climate change.

With this guide, we have brought together both researchers and practitioners to consolidate the best insights and evidence about how to communicate effectively about climate change. We have combined research from the Center for Research on Environmental Decisions (CRED) at The Earth Institute, Columbia University; ecoAmerica; and other institutions with insights that ecoAmerica has gleaned from communicating about climate change and other environmental issues with mainstream Americans and their leaders. This guide presents information on effective climate change communication in a digestible, actionable form to enable communicators to "up their game" when engaging Americans on climate solutions of all types and scales.

This guide isn't just for people who work in environmental organizations. It's also meant for mainstream business leaders, city planners, educators,

nurses, ministers, and journalists—anyone who wants to benefit from cutting-edge research insights and communicate more effectively about climate change. These recommendations can help anyone be a more successful communicator, whether you are a seasoned expert or just getting started. And while this guide is not intended for an international audience, some of its findings may be applicable beyond the United States.

We have organized this guide into four parts ("The Basics," "Crafting Your Message," "Overcoming Barriers," and "Taking It to the Next Level"), each of which builds on the previous. Throughout the guide, we use ***bold italicized text*** to identify important terms and their definitions. We use **bold text** to identify key insights and takeaways critical for communicators to understand. We also include stories about how practitioners and researchers are putting research into practice; these stories are highlighted in sidebars throughout the guide. In addition, we feature in-depth explanations of certain concepts, for communicators interested in diving deeper into some topics, which are also included in sidebars throughout the guide.

Just one word of advice: communicating on climate is not a one-size-fits-all exercise. The United States is a diverse nation, and messages that appeal to one group may alienate others. For any and all of us to connect on climate change, we need to understand our audiences, respect their concerns, and communicate and engage by example, wherever we live and work. With a little practice and forethought, anyone can be an effective climate communicator. We hope this guide will help you do just that.

THE BASICS:
Putting People First

THE BASICS: PUTTING PEOPLE FIRST

The vast majority of Americans report that they have heard of climate change. Yet Americans hold a wide array of opinions and beliefs about the issue.[5] Understanding one's audience, where its members are coming from, and how they arrived there is the first key to unlocking success as a climate communicator. This part of the guide describes why different groups of people have such different responses to climate change information, explains how people process information and make decisions about the issue, and gives tips for understanding one's audience and targeting climate communication accordingly.

Most of the time, people seek out information that supports their existing beliefs and values and reject information that contradicts the beliefs and values that are most important to them.

1 Put Yourself in Your Audience's Shoes

"No one else I know cares about climate change."

Many climate communicators erroneously believe that the main factor shaping people's engagement with climate change is their level of understanding of the science behind it.[6] The latest social science research, however, suggests quite a different story. People interpret new information through the lens of their past experiences, knowledge, and social context. This is particularly the case when it comes to complex scientific and societal issues such as climate change, where objective facts about the state of the world are not the only factors that influence what people believe and how they respond. This section explains how people's values, worldviews, and identities influence their responses to climate change. It also describes how climate communicators can relate that many elements of a comprehensive response to climate change align with Americans' worldviews and that climate solutions can go hand in hand with existing values and goals.

Identify How Values Shape Climate Engagement

Different individuals often come to vastly different conclusions about climate change in part because they hold different core values. ***Values***—such as honesty, hard work, loyalty, privacy, patriotism, fairness, or interdependence—help people make judgments about whether or not climate change is a problem and if and how they should respond.[7]

Most of the time, people seek out information that supports their existing beliefs and values and reject information that contradicts the beliefs

and values that are most important to them.[8] For example, when someone who strongly values personal property rights hears that dunes that will protect the coast against sea level rise will obstruct her waterfront view, an understandable reaction is to dismiss or deny one of the primary factors that would justify the dunes (namely, sea level rise that is being exacerbated by climate change). Likewise, many Americans hold the values implied by the American Dream—such as opportunity, prosperity, and hard work—near and dear to their hearts. Environmental messages with themes that run contrary to these values—the need to sacrifice, reducing material consumption, and doing more with less—may thus be rejected.[9]

Climate communicators should **appeal to values held by their target audience to make it easier for audience members to recognize climate change as a personally meaningful issue.** For example, someone who values national security may be receptive to hearing about how clean energy can reduce dependence on foreign energy sources, thus improving national security. Someone who values prosperity might be motivated by a message that emphasizes how clean energy solutions can unlock new economic opportunities for American families. And information about strengthening community preparedness for future natural disasters may speak well to people who strongly value hard work and self-sufficiency. To learn more about how to identify the values held by your audience, see **SIDEBAR 1: Getting to Know Your Audience**.

Align Climate Messages with Your Audience's Worldviews

People's responses to climate change (and messages about it) are also powerfully influenced by their worldviews. ***Worldviews*** are sets of deeply held beliefs and attitudes about how the world works

and how people should relate to one another. When it comes to climate change, worldviews often act as filters that help people determine whether or not climate change poses a serious risk to society. By affecting our perceptions of risk, worldviews thus shape beliefs about whether and how to respond to climate change.

Let's look at a couple of relevant types of worldviews. The first one relates to a person's beliefs about whether the world should operate through a hierarchical structure (that is, whether people's or groups' ranks should determine their levels of authority) or through a more egalitarian process (a world in which status doesn't matter and all people are equal and treated accordingly). A second relevant worldview relates to how much or little someone believes individuals should be free to pursue their own interests rather than be constrained (to some extent) by considerations of the "greater good." Social scientists refer to the former view as individualism and the latter as communitarianism. These two sets of worldviews powerfully influence individuals' beliefs about climate change.

SIDEBAR 1

Getting to Know Your Audience

Although it is difficult for communicators to uncover *all* of an audience's preexisting worldviews, values, and identities, here are a few steps communicators can take to better understand their audiences.

Do your homework. Communicators should gather as much as information as possible about their audience before interacting with them. Communicators can learn about local concerns and issues by picking up a local newspaper, observing local billboards and ads, and spending time at local stores, restaurants, community centers, libraries, and parks. In addition, communicators can glean insights about broader social, cultural, and political trends and opinions by consulting polling organizations such as the Pew Research Center.[18] If communicators are working with a specific organization, they can also consult the organization's mission statement, local news stories that feature that organization, and the organization's website and social media streams.

Ask questions. To gauge an audience's initial knowledge about climate change, communicators can pose the following sample questions at the beginning of a presentation:

(1) Which of the following statements do you agree with?
a. Climate change is happening now and is caused mainly by human activities.
b. Climate change is happening now and is caused mainly by natural forces.
c. Climate change is *not* happening now.
d. No answer/don't know

(2) Scientists use the term "greenhouse effect" to describe:
a. A hole in Earth's ozone layer, which allows more sunlight to get through
b. The heat-trapping properties of certain gases, such as carbon dioxide (CO_2)
c. The warming effect of pavement and cities
d. No answer/don't know

(3) Do you think that changing weather patterns and an increase in extreme weather events such as storms, floods, and droughts in the United States are caused by climate change?
a. Yes
b. No
c. Maybe
d. No answer/don't know

Answers can be obtained by a quick show of hands.

Develop a dialogue with your audience. For the development of a larger, more comprehensive communication strategy, communicators can use a range of methods, from one-on-one interviews to focus groups and surveys, to determine what their audiences care about, what they already believe, whom they trust most, and so on. See the **FURTHER READINGS** section on Page 82 for more information on how to conduct effective surveys and focus groups.

For example, individuals who believe the world should operate on egalitarian and communitarian principles tend to perceive climate change as something that affects poorer populations or minorities more severely and that will lead to even greater inequality. This view leads such individuals to be generally supportive of broad action on climate change.

In contrast, individuals who believe in the benefits of a hierarchically structured world and who support strong individual rights (even at the expense of the group) are likely to be less supportive of climate action, especially when government-run policies or solutions are highlighted. This is because these individuals may perceive such proposed solutions to climate change as mere excuses for greater (and in their view unnecessary) government regulation and may be afraid that such policies would infringe on their freedoms and rights as citizens.

Communicators can boost engagement by tailoring their communication strategies to the worldviews of their audiences. For example, someone who holds an individualistic worldview and favors self-reliance might react positively to a message that focuses on the capacity to take action on one's own. In contrast, that same person may respond negatively if messages focus only on climate change solutions that require government-organized cooperative action or strict regulation, because these solutions are perceived to weaken the role of individual responsibility.

Understand How Identity Shapes Climate Engagement

An ***identity*** is a person's conception and expression of his or her self and the social groups he or she is part of. Everyone holds multiple identities. For example, someone might identify with a political party, be a member of a religious group, be a resident of a city and region, and be a parent or grandparent. People's identities with certain groups play significant roles in shaping how they think, feel, and respond to climate change. People's occupational identities—such as being a business executive or a farmer—can also play a role in shaping the attitudes and beliefs they hold about climate change. Research suggests that how "top of mind" a certain identity (such as being a parent or a Republican) is in a given moment can play a significant role in shaping how a person responds to messages (and public polling questions) about climate change.[10]

Identity plays a particularly strong role in shaping how people respond to climate change when they have limited knowledge about the complex issue and when they have strongly held identities.[11] For example, in the United States, climate change has become closely associated with political identity.[12] According to the findings of a recent study, when Republicans are reminded that they are Republicans, they report even more skepticism about climate change. And when Democrats are reminded that they are Democrats, they report

SIDEBAR 2

Choosing the Right Messenger for Your Audience

No matter how carefully a communicator designs a message, even a perfectly crafted message is unlikely to succeed if it's delivered by a messenger the audience doesn't trust, admire, or respect.

An ideal messenger is someone whose identities, values, and group affiliations are similar to those of the audience; someone the audience trusts and respects; and someone who can identify and connect with the audience's everyday needs and concerns. Often, it just takes some time spent watching and listening to audience members to identify who they repeat, whose advice they share, who they follow and pay attention to, and thus who might be a good messenger. Those with additional time and resources may want to consider conducting focus groups, in-depth interviews, experiments, and surveys, which can also help identify the right messengers. (See the **FURTHER READINGS** section on Page 82 for resources on how to conduct focus groups and surveys.) CRED research suggests that local messengers (both individuals and institutions) may be more likely to get a response for calls to action on climate change than individuals from outside the community. People are more likely to take action when they feel a strong sense of affiliation with the individual or institution making the request.

Finding the right messenger is especially important because it can help people link new identities to climate change. With the desired identity activated in people's minds, a well-matched communicator can more easily speak to people's values and priorities and make a powerful connection with the audience. (Think of how Mothers Against Drunk Driving succeeds by having mothers talk directly to other mothers.) Keep in mind that messengers may need training in how to deliver messages to their social groups and networks.

even more conviction about the issue.[13] This doesn't mean, however, that there aren't opportunities to help shift the association between particular identities and climate change. For example, Republican leaders such as Christie Todd Whitman, who led the EPA under President George W. Bush, have noted that many Republicans believe that climate change is real and human-caused, even though their party platform often indicates otherwise.[14] Other conservative groups have started talking about climate change in terms of its connections to faith, health, the economy, and national security, a strategy that is likely to bolster support for action on the issue among conservatives (in part by redirecting the current relationship between conservative identity and climate change skepticism).[15]

Communicators should keep in mind that nearly any identity may have both productive and counterproductive implications for climate change engagement. For example, emphasizing someone's identity as a good provider for his or her family may seem like an ideal approach to engaging certain types of people on climate solutions. However, if not approached carefully, talking about this identity in the context of climate change may actually have the opposite effect, making people think about the need to protect their families at the expense of the larger community. Strategies emphasizing the identity of being a good provider for one's family will likely be most effective if they emphasize how taking action on climate can help families achieve other goals, such as keeping kids healthy and saving money on energy bills.[16] It is also possible to create new, positive connections between specific identities and climate solutions. To read about a real-world example of how one initiative is working to link climate change to new identities, see **SIDEBAR 3: Harnessing Identity to Bolster Engagement with Climate Change: The MomentUs Initiative**.

When putting together a communication strategy, communicators should start by identifying core identities of their target audiences. Some of these identities may be obvious, but other identities may be more difficult to recognize. For example, it may be readily apparent that someone is a senior citizen but not immediately clear that he or she is interested in humanitarian work or is very religious. **Communicators should then identify whether a certain identity is already linked to a particular stance on climate change** and, if so, how linking climate change to that identity will affect people's support for or opposition to climate solutions. **No matter what, climate communicators should help people identify how taking or supporting meaningful action on climate change aligns with the identities they hold.**

Appeal to People's Desire to Be "Good People"

Tightly linked to people's values and core identities is their sense of what is morally good and what is morally required of "good people." People are highly

motivated to view themselves as good and moral. Identifying climate change as a "moral issue" may help people tap into these desires.[17] However, communicators should take care to communicate the moral significance of the issue using audience members' values, identities, and priorities rather than their own. Otherwise, a communicator's efforts can come across as moralizing, preaching, or finger wagging.

Climate communicators may also wish to appeal to the ***virtues*** (morally good traits and qualities) that people strive for in their personal and social lives. Previous communication efforts have placed little emphasis on virtues (for example, going above and beyond to help others prepare for extreme weather events). Yet emphasizing virtues may be highly effective in encouraging fundamental and long-term change in people's responses to climate change, in part because doing so can help people develop concrete projects that provide concrete personal results. **In short, to encourage long-term engagement, communicators should develop messages that align with their audiences' moral values and that provide opportunities for people to put their virtues into practice.** For more information on how to develop messages that resonate with your audience's moral values, see **SIDEBAR 4: Understanding and Connecting with Moral Foundations.**

SIDEBAR 3

Harnessing Identity to Bolster Engagement with Climate Change: the Momentus Initiative

One of the greatest challenges that climate communicators face is that climate change is so tightly linked to politics and political identity. But climate change doesn't have to just be about politics. Responding to climate change can also be about being a good citizen, living out one's faith, doing good business, staying healthy, or being an engaged teacher or student. This is a core motivating idea behind MomentUs, a new ecoAmerica initiative designed to catalyze a game-changing increase in the base of public support for climate solutions in the United States. MomentUs was conceived on the premise that Americans will act on climate change if they come to understand how it is relevant to the many identities they hold outside of the voting booth. MomentUs empowers leaders who interact with Americans where they work, live, play, pray, and learn with research-based guidance on climate communication to help facilitate this shift in understanding among the American public. Through peer-to-peer engagement, conferences, and training, MomentUs encourages leaders to harness the identities they share with their audiences to build trust, credibility, and consequently support for climate solutions. To learn more about MomentUs, visit *momentus.org*.

SIDEBAR 4

Understanding and Connecting with Moral Foundations

Researchers studying moral judgment have established six sets of ***moral foundations*** that drive people's understanding of what is "good" or "moral," as outlined in **TABLE 1: Moral Foundations and their Characteristic Emotions, Virtues, and Examples**. For example, the moral foundation known as "care/harm" encompasses kindness, gentleness, and nurturance, while the "fairness/cheating" foundation encompasses fairness, justice, and trustworthiness.[19] Some moral foundations resonate more strongly with some audiences than with others. For example, psychologists at the University of Virginia found that liberals showed greater endorsement and use of the care/harm and fairness/cheating moral foundations, whereas conservatives tended to use and endorse all moral foundations more equally.[20]

In another study, researchers at the University of California–Berkeley found that environmental messages tend to emphasize care/harm, a moral foundation important to many liberals. This may explain why liberals are sometimes more receptive to environmental messages than conservatives.[21] However, the researchers also found that ***reframing*** environmental issues in terms of sanctity/degradation increased conservatives' concern. **This suggests that reframing the same issue using different moral foundations can have a significant impact on the diversity of individuals and groups who will show concern about it.** For more information on framing, see **SECTION 5: Connect Climate Change to Issues That Matter to Your Audience**.

TABLE 1

Moral Foundations and their Characteristic Emotions, Virtues, and Examples

The table below lists six moral foundations along with the characteristic emotions, relevant virtues, and climate communication themes and concepts associated with each.[22] Climate communicators can decide which climate communication themes and concepts to emphasize with an audience depending on the moral foundations they think the audience will resonate with most.

	Characteristic emotions	Relevant virtues	Examples of climate communication themes and concepts
Care/Harm	compassion for victim; anger at perpetrator	caring, kindness	keeping children safe from climate's health effects; "saving the environment;" protecting polar bears and other wildlife
Fairness/ Cheating	anger, gratitude, guilt	fairness, justice, trustworthiness	effect of climate change on farmers in developing nations; oil companies' pollution and profits
Loyalty/ Betrayal	group pride; rage at traitors	loyalty, patriotism, self-sacrifice	preserving America's natural wonders; being good stewards of American nature
Authority/ Subversion	respect, fear	obedience, deference	following the advice of or obeying respected professionals, business leaders, or the pope
Sanctity/ Degradation	disgust, adoration	temperance, chastity, piety, cleanliness	ensuring clean air and clean water
Liberty/ Oppression	joy, loathing	independence, respect for autonomy, rationality	self-sufficient forms of energy

Source: Adapted from Haidt, J. (2012). *The righteous mind: Why good people are divided by politics and religion.* New York: Pantheon.

TIPS Put Yourself in Your Audience's Shoes

Consider the following questions when thinking about audiences and the role that existing beliefs and attitudes play in shaping how they respond to climate change.

- Who is your target audience?
- What relevant beliefs does the target audience already hold? What do you know about audience members' core values and worldviews? How can you help people recognize where climate change solutions can line up with those values and worldviews? (See **SIDEBAR 1: Getting to Know Your Audience,** for tips on finding this information.)
- What identities do your audience members hold? Are they religious? Liberal? Conservative? Do they work on farms? On Wall Street? Are they single or married? Do they have children or grandchildren? Will reminding people of these identities make them more or less likely to want to positively engage with climate change?
- What virtues and moral values do your audience members find most important? How can you frame your message in a way that shows how doing something about climate change can help people put those virtues into practice?
- What moral foundations might be most important to your audience? (See **TABLE 1: Moral Foundations and their Characteristic Emotions, Virtues, and Examples** and **SIDEBAR 4: Understanding and Connecting with Moral Foundations**.) How can you show that climate change issues relate to those moral foundations?
- Who does your audience trust and respect? Can any of these individuals serve as messengers for a climate communication strategy? (See **SIDEBAR 2: Choosing the Right Messenger for Your Audience**.)

2 Channel the Power of Groups

"Well, if my church is getting involved…"

At their core, humans are social beings, and their identities and memberships in social groups and networks play a seminal role in shaping their attitudes and behaviors. This section explains how people behave and process information differently in groups, which groups are most likely to help catalyze climate engagement, and how communicators can harness groups and social networks to keep people engaged on climate change in the long run.

How People Think and Behave Differently in Groups

People often think and behave differently when they're physically part of a group or reminded of their membership in a group. When people make decisions or process information as part of a group, their goals may shift toward promoting outcomes that are good for the group rather than promoting outcomes that are good for only themselves as individuals. These effects are driven by a number of mechanisms unique to group settings, including an enhanced sense of affiliation and connection with other people, an increased tendency to follow the group's norms, a weakened focus on personal identities and goals, and the desire to avoid social

SIDEBAR 5

Talking about Climate Change in Group Settings

People process information about climate change differently when they engage with it in a group setting, such as a focus group or neighborhood meeting. In groups, people often consider a wider range of possible options and show deeper engagement with arguments and various courses of actions that are proposed. Australian researchers Anne Pisarski and Peta Ashworth have found that facilitated small-group discussions can produce positive changes in climate attitudes and support for policy solutions.[25] Their "Citizens' Round Tables" provide non-expert members of the public an opportunity to voice their own opinions, ask questions without fear of ridicule, and see themselves as engaged citizens trying to tackle this large problem.

As with other successful group-based strategies, Citizens' Round Tables start with an interactive discussion that provides an opportunity for group members to bond with one another and express their initial attitudes and beliefs. Only once people are comfortable and engaged do they receive a short, focused presentation from a climate scientist. Using multiple formats and media (video, PowerPoint, fact sheets), presenters give participants accurate information about various energy futures and their impacts on climate change. Finally, participants engage in a second discussion with each other and with the scientists in the room, so they can integrate and consider the information they have been presented. Although time-intensive, such focused, group-based approaches to climate change communication can be highly effective. Communicators may wish to keep in mind that **involving highly influential members of society, including policy makers and community leaders, may be an especially productive approach to promoting broader diffusion**.

Climate communicators can channel the influence of groups by helping people view their actions and responses to climate change as part of a larger group effort, whether that group is a neighborhood, a company, or a faith-based organization. Framing climate change as a group challenge is particularly important given the large-scale nature of the problem (which can activate feelings of inefficacy and despair if people focus solely on their own contributions).[23] Climate communicators may also wish to create opportunities to allow people in a community to discuss climate change and climate solutions in group settings. (See **SIDEBAR 5: Talking about Climate Change in Group Settings**.)

Mobilize Social Groups and Networks

One powerful way to keep people engaged in the long term is to weave climate change into the activities of existing social groups and networks, such as neighborhood associations, religious groups, clubs, parent–teacher associations, or company departments. People are more likely to become engaged on an issue when a group they are a part of—and that's important to them—cares about it. The most relevant groups are often relatively small and geographically local, such as a neighborhood or a group of work colleagues. Dispersed but highly interconnected groups (such as virtual, internet-based groups through

Facebook and other social media sites) may also prove fruitful for climate engagement.

Groups and social networks that are particularly powerful are those that hold strong, shared beliefs about questions of "right and wrong." These groups are often able to encourage members to follow group norms of behavior, meaning that a shift in thinking or acting among group leaders can have effects on many others. (For more information on norms, see **SECTION 10: Make Behavior Change Easy**.) Communicators can be particularly effective by identifying and working with such groups, as well as with those that are ready to take action on climate change but are not yet doing so. Providing climate communication and engagement resources to leaders within these groups can be an especially effective strategy for eventually activating the group's entire membership.[24]

SIDEBAR 6

Getting New Constituencies Talking about Climate Change: The Climate Conversations Project

Congregations across Minnesota are holding small, peer-to-peer conversations about climate change as part of a new initiative called the Climate Conversations Project.[26] The conversations, which are led by Minnesota Interfaith Power & Light with assistance from Climate Access and other researchers, are designed to increase engagement around climate change among those who aren't already talking about and acting on the issue. Facilitators pose guiding questions that help participants uncover why climate change is personally relevant, how it relates to what they already value, and what they can do to take action on the issue. The inspiration for the project came from the marriage equality movement, which used similar conversations to catalyze changes in people's beliefs around marriage for gay couples.[27] Initiatives like these have shown that people are more likely to become engaged on an issue when it is brought onto their radar by a group to which they belong and that they deem important.

SIDEBAR 7

Group Affiliation and Cooperation

CRED researchers designed an experiment to measure the effects of social goals, in particular the effect of affiliation on cooperation.[28] Students were split randomly into four-person groups (analogous to four large greenhouse gas emitters). The researchers created different levels of affiliation among group members (temporary, short-lived connections). Groups then played a game that rewarded those who chose to defect rather than cooperate. CRED researchers found the following: as affiliation increased, so did cooperation; affiliation made social goals (for instance, concern for others) a greater priority; and the added benefit of cooperation more than made up for the sacrifice (in this case, monetary sacrifice). Students reported that they felt good about cooperating. Communicators who want to promote cooperation should try to activate concern for others by combining social and economic appeals and by emphasizing an affiliation among group participants. This approach can be more effective than offering economic incentives alone.

A related study shows that when identification with one's group is very high, people are willing to overcompensate for defectors within their group (that is, group members who act selfishly and don't support the greater good of the group) at a personal cost and even when defectors end up doing better than they do. At least part of the motivation for the person overcompensating is a desire to be perceived as "ethical" and as a role model for the not-so-good group member. Tapping into group affiliation and identity not only can lead to greater engagement and cooperation among group members but can also be a powerful tool to help groups reach tipping points in behaviors even when some group members are defecting (not doing the right thing for climate change).[29]

TIPS Channel the Power of Groups

Most Americans are part of at least one formal or informal social group, like a company department, faith or religious organization, parenting group, professional association, or athletic group. These groups can serve as powerful conduits for climate engagement. Consider the following questions regarding the role of identity and goals:

- What relevant social networks (parents of children in a particular school, for example) and groups (religious denominations or congregations, sports clubs, companies, the Rotary Club) is your audience already a part of?
- Who are the leaders of these groups? Would any of them be amenable to serving as a messenger for your climate communications strategy? (See **SIDEBAR 2: Choosing the Right Messenger for Your Audience**.)
- What values of these networks and groups align with climate solutions?
- How can your audience's existing group identities and networks be leveraged to make climate change salient and personally relevant?
- How can you strengthen individuals' affiliations with each other and thus increase their likelihood of acting cooperatively?
- What opportunities can you create that will allow people in your audience or community to discuss climate change and to brainstorm possible solutions as a group? (See **SIDEBAR 5: Talking about Climate Change in Group Settings.**)

CRAFTING YOUR MESSAGE:

Solutions, Impacts, Framing, and Imagery

CRAFTING YOUR MESSAGE: SOLUTIONS, IMPACTS, FRAMING, AND IMAGERY

Starting with people and their values, worldviews, identities, and group memberships is a critical first step in effective climate change communication. But climate communicators also need to understand how to craft messages that incorporate both climate impacts and climate solutions and that show how climate change relates to other issues people care about. This part of the guide explains why it's essential to keep solutions and benefits front and center, provides tips about how to communicate about climate impacts in a way that both personalizes the issue and empowers people to act, describes how to link climate change to other issues audiences care about through framing, and overviews how to use imagery and storytelling to bolster climate engagement.

Solutions should be described in a way that identifies specific roles for individuals and local communities to play, either in the development or implementation of proposed strategies.

3 Emphasize Solutions and Benefits

"This is just so depressing."

Recent research indicates that a critical barrier to greater public engagement on climate change is the perception that the problem is simply too big to solve.[30] *People realize that confronting climate change will require collective and political action, yet many have little faith in one another and even less in government to solve the problem.*[31] *Not believing that climate change can be solved can paralyze people through apathy and hopelessness and eventually create a self-fulfilling prophecy. To avoid this, climate communicators should take care to put climate solutions and benefits of action front and center. This section describes how "solutions-first" messages can foster engagement, explains why communicators need to help their audiences feel like they can be part of the solution, and helps communicators identify the scale of solutions they should communicate.*

Lead with Solutions to Boost Engagement

Climate communicators often assume that people have to be convinced that climate change is happening before they will support solutions or

take action. However, this is not the only way to approach the issue. In fact, **leading with solutions, rather than the problem, often makes it easier for people to accept that climate change exists.**[32] **This may be especially true when people hear about strategies to prevent or prepare for climate change that align with their values and worldviews.**

Solutions imply action and opportunity. They also provide a goal to reach for, individually and collectively. **When communicators help people envision solutions to climate change, they provide a positive vision of what the future could be like. This can help quell counterproductive feelings of hopelessness and dread.** Images of possible new energy production mechanisms and systems, for example, can provide people with a buffer against the otherwise paralyzing negative emotions about climate.[33] "Solutions-first" messages may also help promote positive emotional responses, including pride and hope, that can motivate action and engagement. It is important to identify solutions that match the level of action that the audience can take. One way to do this is to generate strategies and activities through a participatory process involving representatives of all relevant parties. The Red Cross Red Crescent Climate Centre has applied this approach in developing an early warning/early action system with residents along the Senegal River.[34] Through participatory games, mapping exercises, and discussion, community members generated more than three hundred new ideas for possible actions to take prior to and during a flooding event.

Show Your Audience Members How They Can Become Part of the Solution

People are unlikely to take action when they don't believe an issue can be solved—either through their own or others' efforts. **Successful communication must therefore build confidence that climate change can be addressed.** People's sense of personal and collective ***efficacy***—the capacity and willingness to successfully confront the challenge—is part of what ultimately drives how they respond to the threat of climate change.[35]

Generating positive emotional responses and a sense of efficacy requires that people believe two things about proposed solutions: first, that proposed actions, technologies, or policies can actually solve the problem; and second, that those solutions will actually be implemented. Equally important, solutions should be described in a way that identifies specific roles for individuals and local communities to play, either in the development or implementation of proposed strategies. For large-scale political solutions, this role may be as motivators of change, being part of an engaged citizenry, or taking political and civic action. For more local-scale solutions, the engagement may be more direct: from shifting consumption practices to working with local leaders to encouraging new business models to changing one's own behavior and encouraging one's friends and family to do the same.[36]

Another strategy for helping audience members understand how they can be a part of the solution is discussing the ***behavioral wedge***. The "behavioral wedge" is a term coined by researchers who found that household behavior could make a substantial difference in reducing greenhouse gas emissions as part of a comprehensive climate action plan that includes a number of large-scale technological innovations and responsible policy making to decrease emissions to 80 percent below 1990 levels.[37] Adding a behavioral/personal action component to the wedge approach would mean that in the U.S. residential sector alone, emissions could be reduced in an amount equivalent to the total emissions of France. The majority of this potential comes from

the adoption of energy-efficient behavior and technologies at the household level. Emphasizing the scale of impact that personal choices can have may help inspire audiences to take action.

Highlight the Benefits of Taking Action

Climate change is not an isolated issue. The impacts of climate change extend to the economy, public health, agricultural systems, national security, and even psychological well-being. This also means that responding to climate change can bring benefits to other areas of society. For example, responding to climate change can bolster our health and well-being, strengthen community cohesion, and catalyze economic opportunities in the United States and across the world. **Research indicates that emphasizing co-benefits, especially when they are immediate and personally relevant to audience members, may be an especially effective way to get more people on board with solutions.**[38]

Align Solutions with Your Audience's Values and Priorities

As discussed throughout this guide, people are more likely to respond positively to climate change communication efforts that speak directly to their values. This fact is especially true for communicating about solutions. When proposed solutions align with people's values and worldviews,

people are more likely to endorse both the solution and the existence of climate change.[39] However, the reverse is equally true: when there is a mismatch between the solution (such as greater regulation by federal government agencies) and people's values or worldviews (such as a strong focus on individualism rather than collectivism), people are likely to reject both the solution and the larger issue (even those who might otherwise believe climate change to be a problem). Communicators may also wish to consider using traditionally masculine cultural themes, such as boldness, scale, and dominance, when talking about climate solutions to align with the values and worldviews of, for instance, self-reliance, independence, or patriotism.[40]

Communication efforts should thus:

- Help people **identify how a proposed solution allows them to pursue the priorities and values that they already care about**
- **Link solutions to values that are widely shared** (such as patriotism, independence, and freedom in the United States)
- **Incorporate and account for values and identities in the design and implementation of climate solutions.**[41]

Presenting solutions that align with people's values and goals is also likely to generate greater engagement because individuals, communities, businesses, and organizations see how these solutions will benefit them. This may be particularly true with local-scale or sector-specific solutions. For example, recent efforts to sequester carbon in grasslands and rangelands could motivate individuals and communities who might otherwise be skeptical of climate science and policy with the use of associated financial incentives. (For example, ranchers could be paid to manage their lands in ways that increase how much carbon is sequestered in the ground.)[42] Other research suggests that presenting wind and solar energy as opportunities to bolster the American manufacturing base and to lessen U.S. dependence on foreign oil, which are key priorities for some Americans, could be especially effective in motivating support among some conservatives.[43]

Scale from Local to Global Solutions

Communicators should strive to highlight the personal and local aspects of climate change when possible, with regard to both climate impacts and climate solutions. Connecting local-scale solutions to local-scale impacts helps people see and recognize cause-and-effect relationships between climate actions and outcomes for themselves, something that is harder to communicate when talking about solutions to an issue perceived as far off in time and space. Ideally, proposed solutions are win-win: they both help combat climate change *and* address visible, well-known local issues or local climate impacts.

Solutions should also match the impact and scale of the issue: talking about hyperlocal solutions but framing climate change as a global phenomenon (or vice versa, focusing on local impacts but promoting only national or global policy responses) may backfire by confusing people or making them skeptical that the solutions and problem actually fit one another.

Put Technological Solutions in Context

Highlighting solutions to climate change is a powerful route to engaging people on the issue. However, not all solutions are created equal, and communicators need to be careful not to induce backfire effects by promoting solutions that are mismatched to the scale or time frame of the problem. Some proposed solutions (such as nuclear fusion) could actually

decrease motivation for individual-level action. This is particularly true of technological solutions, which can undermine engagement by promoting false beliefs of "technosalvation" or "solutionism" and can reduce motivation to take personal or collective responsibility.[44] **Solutions that are not plausible at the time of communication (such as immediate widespread adoption of distributed renewable energy systems) should be promoted along with, not as a replacement for, the individual- and local-scale solutions that will also need to take place.** Communicators should also acknowledge that some technological solutions can have (or can be perceived as having) unintended dangerous side effects and should be mindful of people's possible fears associated with engineering innovations. ■

The following table provides examples of climate solutions for various sectors.

TABLE 2

Climate Solutions and Mechanisms to Facilitate Them

Sector	Suggested Climate Solutions and Mechanisms
Energy production	• increasing renewable heat and power (solar, wind, hydropower, geothermal, and bioenergy) • reducing subsidies for fossil fuels • taxing fossil fuels • implementing incentives or requirements to source electricity from renewable/clean sources (such as the Renewable Portfolio Standard) • providing subsidies for producers of renewable energy • facilitating carbon dioxide capture and storage (CCS) • implementing power plant emissions limits • switching from coal to natural gas in the interim • using nuclear power in the interim
Transportation	• using fuel-efficient vehicles, hybrid and electric vehicles, and cleaner diesel vehicles • using biofuels • using and improving public transportation • using nonmotorized forms of transportation (walking and biking) • improving and implementing fuel economy standards for vehicles • changing transportation and land use planning to influence mobility needs • taxing vehicle purchase, registration, and use • pricing road usage and parking

Buildings and homes	• using more efficient lighting, such as CFLs and LEDs • using daylight instead of artificial light • using more efficient electrical appliances and heating and cooling devices • improving insulation • using solar heating and cooling • using appliance standards and labeling that show energy usage • encouraging consumers to use less energy during peak hours • implementing building codes and certification • using smart meters that provide feedback and control
Industry	• recovering heat and power from manufacturing processes • recycling materials • replacing materials with climate-friendly materials • controlling emissions of all greenhouse gases that contribute to climate change (for example, methane and nitrous oxide) • creating and using more efficient electrical equipment • facilitating voluntary agreements with clear targets to reduce pollution • implementing cap and trade systems (like the Regional Greenhouse Gas Initiative in the Northeast)
Food and agriculture	• improving crop and grazing land management to increase the amount of carbon soil storage • using fertilizer more efficiently to reduce nitrous oxide • irrigating crops more efficiently • improving livestock and manure management to reduce emissions of methane • improving energy efficiency in the agricultural sector • providing incentives and regulation for improved land management
Forestry/ forests	• facilitating afforestation (planting trees where there didn't used to be trees) and reforestation (planting trees where trees have been cut down) • using forestry products to create bioenergy to replace the use of coal and oil • facilitating and improving land-use regulation • facilitating and improving forest management and reducing deforestation
Waste	• composting organic materials such as food scraps • recycling and reducing waste • recovering methane pollution produced by landfills • capturing energy produced during waste incineration • controlling wastewater treatment • facilitating regulations and incentives for better waste and wastewater management

Note: The guide authors do not endorse these solutions and mechanisms. Rather, they are suggestions for policies and actions that climate communicators may wish to highlight in their climate communication strategies.

Source: Adapted from Table SPM.4: "Selected Examples of Key Sectoral Mitigation/Adaptation Technologies, Policies and Measures, Constraints and Opportunities" in the Intergovernmental Panel on Climate Change's 2007 Synthesis Report. Available at: www.ipcc.ch/publications_and_data/ar4/syr/en/spms4.html#table-spm-5.

TIPS Emphasize Solutions and Benefits

Helping people imagine a brighter future for their family and community without dangerous climate impacts should be a central goal for climate communicators. Doing so will boost perceptions of personal and collective efficacy and circumvent potential roadblocks to engagement and action, such as fatalism, apathy, doubt, and denial. Providing your audience with concrete, plausible solutions to climate change is one way to accomplish this goal.

Moreover, when people believe there are solutions available, they are more likely to perceive climate change as a problem worth addressing. Whatever solution your organization promotes (see **TABLE 2: Climate Solutions and Mechanisms to Facilitate Them** for ideas), communication efforts should emphasize the role that individuals and local communities have to play in making those possibilities a reality and the benefits that they will accrue as a result of responding to the issue. When developing solutions-based messaging, communicators should consider the following questions:

- Does your strategy highlight solutions to climate change or does it focus exclusively on making people understand the problem?
- Can you clearly communicate the personal benefits of the proposed solution? Do these benefits seem tangible and immediate?
- Are you framing solutions in a way that aligns with the values and identities held by your target audience? Are you communicating how a proposed solution allows your audience to pursue the goals and values they already care about?
- Do the solutions being proposed involve or require individual-level or community-level action? Does your communication make clear which type of action (if any) is required of the audience to whom you're communicating?
- Are you communicating solutions that are plausible at the time of communication?
- Are you being careful not to underpromote the role that individuals and communities need to play, even for large-scale technological solutions?
- Are you focusing on the local aspects of solutions whenever possible?

Bring Climate Impacts Close to Home

"But climate change isn't affecting me."

Over the past few years, the narrative about climate change impacts has shifted. Where communicators once focused on polar bears losing their habitat in the Arctic as a key impact of climate change, more communicators are now focusing on impacts that climate change–induced extreme weather will have around the United States. Despite such recent efforts to make climate impacts resonate better with audiences, many people continue to perceive climate change as a distant issue that won't affect them personally.[45] *This section describes how climate communicators can encourage people to respond to climate change by focusing on local impacts, highlighting personal experience, focusing on the "what" and not the "when," and pairing impacts with solutions.*

Focus on Local Impacts

People have a hard time thinking about—or acting on—things and events that are perceived as far in the future, physically distant, happening to other people, or involving uncertainty. Psychologists refer to these as dimensions of ***psychological distance***.[46] Climate change is a prime example of a psychologically distant phenomenon. Thus our minds are not designed to immediately react to climate change, which can weaken motivation to take action.

To overcome these challenges, communicators can use vivid imagery and messages to help people identify the locally relevant, personally experienced consequences and impacts that climate change is already causing.[47] (For more on the use of imagery in climate change communication, see **SECTION 6: Use Images and Stories to Make Climate Change Real**.) For example, the concept of rising sea levels may feel distant or abstract to many people, even those who live on or near the coast. To make this impact more concrete, communicators can describe future water levels in terms of recent flood events that are vivid and easily imagined.[48] Communicators might describe how climate change risks could put parts of a city that were flooded during a past storm underwater more frequently or even permanently. Climate communicators can

SIDEBAR 8

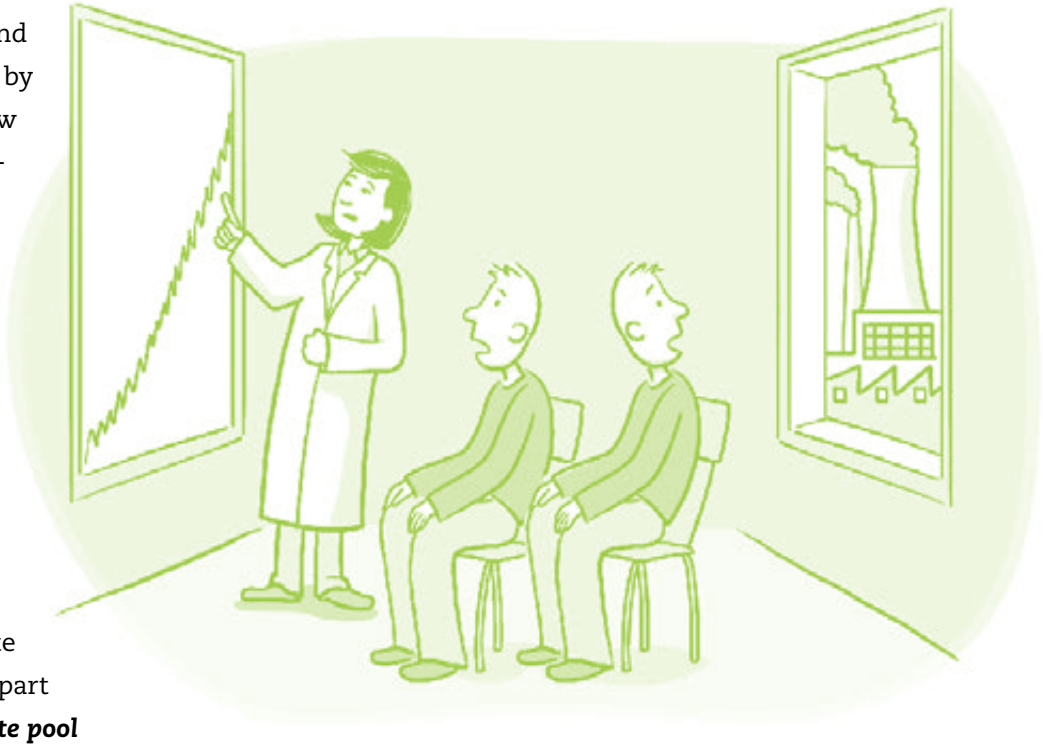
Making Climate Change Concrete through Experience, Real or Virtual

The most vivid way for people to learn about the impacts of climate change may simply be to experience them. Seeing water lapping at one's doorstep removes the psychological distance of flooding in every way: it is certain, it has been pulled out of the future and into the present, and it is physically close and personal. Some evidence suggests that communities that are already experiencing flooding may be better able to connect these events with climate change. Indeed, flood experience has been shown to increase concern about climate change and to reduce feelings of uncertainty.[57]

However, not all communities experience hazardous events that connect easily back to climate change. Moreover, waiting for a natural hazard to strike is of course a costly way to bring climate change psychologically closer to the public. **Personal experience with flood events is only one way to make climate change feel closer and more concrete. Other ways include asking people to detail the specific actions they would take in the event of a hazard, listing the individual effects the hazard is likely to have on their homes, facilitating participation in evacuation drills or mock emergency events, and encouraging people to update their disaster preparedness kits.**

Many groups have made sea level rise psychologically closer to the public by creating "blue line" projects that pair scientists with artists to paint the height of future sea levels on waterfront buildings and infrastructure. Seeing a line of blue paint on telephone poles, mailboxes, and downtown buildings provides a very concrete image of what sea level rise will mean for individuals and communities. Besides increasing support for global efforts to reduce climate change, this type of awareness-raising project has the additional advantage of promoting local preparedness, such as improving building codes or even retreating from flood-prone areas. However, climate communicators should take care to acknowledge the emotional and psychological effects that result from experiencing climate change directly or virtually and should build people's confidence that they can effectively take action on the issue.[58]

also use interactive tools and maps such as those created by Climate Central, which allow people to visualize how different degrees of sea level rise will affect their own neighborhoods.[49]



Highlight Personal Experience

People's lives are filled with immediate and near-term concerns, most of which are perceived as more pressing than climate change. This is the case in part because people have a ***finite pool of worry***, meaning they are able to worry about only so much at any given point. Yet it turns out that many people, including most Americans, are already feeling the negative impacts of climate change, even if they don't associate those impacts with climate change.[50] **Helping people identify the local and personally relevant impacts of climate change—including loss of property from intensified extreme weather events and the greater spread of infectious diseases—may go a long way in making the problem salient and urgent for more people.**

In addition, highlighting people's personal experience with current, local impacts of climate change in general is likely to increase audiences' engagement with the issue more so than communicating additional abstract facts and figures. This is in part because direct experience with climate impacts affects people's perceptions of the risk of climate change and how worried they are about the issue. Researchers in the United Kingdom, for instance, have found that people who have experienced major flooding events report higher concern about climate change and are more certain that it is happening.[51] Other research has found that the effects of personal experience of climate impacts are particularly strong among individuals and communities that tend to be more skeptical of climate change.[52]

Climate communicators should keep in mind, however, that there is a fine line between productively engaging people through their personal experiences with climate-related impacts and unintentionally leading people away from positive engagement with the issue. **Making the issue "too real and too scary" repeatedly is a possibility and can lead to denial of the problem.**

Climate communicators should also exercise caution in attributing specific extreme weather events or other environmental and societal changes to climate change. While scientists know that the frequency and/or severity of many extreme weather events—such as storms, droughts, floods, and extreme temperatures—are increasing with climate change, scientists are unable to attribute any one specific event to climate change.[53] One useful metaphor to

help explain this phenomenon is that of a baseball player using steroids. While no one can know whether any particular home run is directly attributable to a player's use of steroids, one can be reasonably sure that the likelihood of the baseball player hitting home runs is greater as a result of his use of steroids.

Pair Impacts with Solutions to Avoid Emotional Numbing

Communication strategies and messages that make climate change concrete and vivid without simultaneously building feelings of hope, pride, and efficacy are unlikely to be effective, as they are likely to lead to emotional overload and paralysis. If communication efforts repeatedly expose people to emotionally draining messages and images, audiences may eventually stop responding emotionally altogether, a phenomenon that psychologists call ***emotional numbing***.[54] **One key to avoiding these effects is to tie concrete, personal climate impacts to immediate, local solutions already available to individuals and communities.** Using the same overarching frame (for example, public health or clean energy jobs) when communicating challenges and potential solutions can be an especially effective way to make sure the audience both understands the issue and feels empowered to be part of the solution. For example, talking about negative economic impacts of extreme weather could be paired with highlighting opportunities for entire new job sectors in renewable energy to generate feelings of hope and efficacy. See **SECTION 5: Connect Climate Change to Issues That Matter to Your Audience** for more information about using frames effectively.

If communication efforts repeatedly expose people to emotionally draining messages and images, audiences may eventually stop responding emotionally altogether.

Focus on the "What," Not the "When"

One of the mistakes communicators often make is assuming that people will interpret and understand numerical and statistical information exactly as communicators intended. In reality, people often distort, misunderstand, or simply ignore such information, particularly information about mathematical probabilities. **To overcome these obstacles, communicators should focus on the consequences of particular impacts or events (such as a drought or major flood) rather than on the probability or likelihood that such an impact will occur within a particular period of time** (such as this hurricane season or next year). Similarly, common terms used by scientists to describe major events, such as "hundred-year flood," can make people think they are safer than they are in the few years immediately following such an event. Again, climate **communicators should avoid terms like these and instead focus on describing what *will* happen the next time that impact occurs locally.**

Be Sensitive to Recent Losses and "Near Misses"

Highlighting recent losses and major climate-related events can help people understand why climate change is personally relevant and requires immediate action. Yet highlighting these types of events can also quickly backfire if people think that communicators are trying to exploit recent tragedies and fragile emotions to pursue their own ends. Communicators can avoid these negative effects by helping people move quickly from identifying local impacts to embracing local solutions, particularly those that have to do with preparedness. **People will take risks more seriously—and be more likely to act—when they perceive the impacts of climate change as local and personal *and* when they understand concrete steps they can take to prepare for or prevent those impacts moving forward.**

On the other hand, recent "near misses" (as occurred for many people in the New York City area with Hurricane Irene) can push people in the opposite direction. Near-miss events—when people are warned of an impending storm or other negative impact that ends up not happening—can decrease people's trust in communicators and scientists, increase resistance to paying up-front costs for preparedness, and make people generally complacent about future warnings. Specifically, when near misses are interpreted as disasters that *did not occur* (versus events that *almost happened*), people underestimate the danger of subsequent hazardous situations and make riskier decisions.[55] **When interacting with individuals or communities that have recently experienced near misses or false alarms, communicators should be careful to focus people on *what they need to do* to keep themselves safe when the next storm, drought, or other impact does hit, regardless of exactly *when* the negative event will happen.** ■

SIDEBAR 9

The Psychological Impacts of Climate Change

When people think about climate change, they often think about the impacts it will have on the weather and the physical environment. This can make climate change seem distant and abstract. Yet climate change will also have significant impacts on our mental health. For example, as climate change progresses, experts expect heightened levels of stress, anxiety, depression, and post-traumatic stress disorder, as well as a loss of community identity and increases in interpersonal aggression.[59] Communicating about these more tangible impacts of climate change may help personalize the issue and motivate people to take action to prepare for and prevent these effects. As with any climate communication, communicators should take care to balance a focus on the psychological impacts of climate change with a focus on how individuals and communities can prepare for and prevent them.

TIPS Bring Climate Impacts Close to Home

For most people, climate change is perceived as a distant threat. Even when events made more severe by climate change—such as storm surges or extreme droughts—occur, many people may not readily connect them to human-induced climate change. Communicators should strive to highlight local-scale impacts that are already occurring—and that will occur in the future—as a result of climate change. However, it is important that communicators also explain the need for and build people's confidence in the possibility of preparedness and prevention responses by individuals and communities.[56]

Consider the following questions as you are putting together your communication strategy about climate impacts:

- Are you helping people identify the locally relevant consequences and impacts that climate change is already causing?
- Are you pairing climate impacts with solutions to avoid emotional numbing and to bolster engagement?
- Are you being sensitive to people's recent losses when discussing local impacts and hazards from climate change?
- Are you focusing on the "what" rather than the "when" for disasters and avoiding terms like "hundred-year-flood"?
- Have members of your target audience recently experienced one or more near misses or false alarms involving major hazardous events? If so, how will you confront the challenges this can pose to future decision making?
- Does your strategy help people identify ways to prepare for future events and impacts?
- Are you employing strategies that focus on resilience and preparedness to help make climate change more concrete and to help guide people toward action?

Connect Climate Change to Issues That Matter to Your Audience

"I just don't get why this matters to me."

Effective climate change communication helps people make the connection between their personal concerns and climate change. To tell a compelling story, communicators need to make decisions about what information or perspectives to highlight through the process of framing. This section helps communicators understand how to find and use frames that highlight information that will be most meaningful for their audiences and will be most likely to generate meaningful engagement.

Connect Climate Change to Issues That Matter to Your Audience Using Content Frames

Climate communicators are more successful when they show how climate change connects to issues or concerns that their audiences care about. ***Content frames*** describe who, what, why, and how. Content frames might highlight, for example, public health implications of climate change, the relationship between climate change and national security, or how climate change (and climate solutions) affects personal health and family well-being. One frame that has received increasing attention is a human health frame, especially with regard to the Environmental Protection Agency's regulations for emissions from coal-fired power plants. To learn more about framing climate change in terms of human health, see **SIDEBAR 10: Using a Public Health Frame to Talk about Climate Change**. Unsurprisingly, different content frames speak to different audiences and motivations. (See **SIDEBAR 11: Framing and the Politics of Carbon**.)[60]

Provide a Coherent Narrative: Match Audience Priorities with Structure Frames

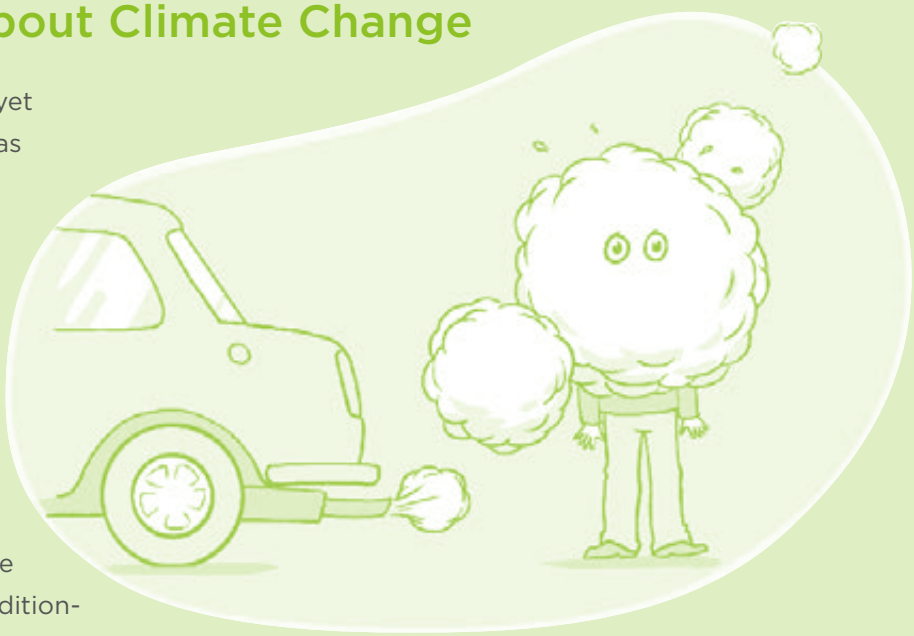
While content frames provide the outline of the narrative a communicator will develop about climate change, another type of frame can shape how particular aspects of the problem or solution are presented. Such frames, which usually have to do with subtle yet powerful changes in wording, are called ***structure frames***.

Structure frames shape how an audience relates to a message by emphasizing "when," "where," and "how many." For example, communicators can frame climate change in terms of potential losses versus gains, local versus nonlocal impacts, the present versus the future, and preventing bad outcomes versus promoting positive outcomes.[61] Impacts on nonhuman species, for instance, can be discussed in terms of "saving biodiversity" (gain frame) or "species extinction" (loss frame).

Researchers have identified a number of structure frames that play a strong role in affecting how people perceive climate change. Communicators

SIDEBAR 10

Using a Public Health Frame to Talk about Climate Change



Many Americans do not yet perceive climate change as a threat to human health. Drawing attention to the connections between climate change and human health may be an effective method for elevating public concern about climate change in the United States. This is especially true for people and groups that have traditionally been skeptical about the negative environmental effects of climate change.[66] By articulating the serious health consequences of climate change and fossil fuel burning, such as more severe and widespread asthma and allergies, more illness and death from extreme heat, and the increased spread of disease, communicators can help frame climate change as a concrete, personal concern for everyone. Health-based messages are often even more effective when they include real stories about people suffering from asthma or heat-related illnesses and when they include statistics from credible, nonpartisan sources like the American Lung Association.[67] Another best practice is to describe how climate change will impact the lives of the most vulnerable populations, like children and the elderly.[68]

Framing solutions to climate change—such as advancing the clean energy economy—in terms of health benefits may also help increase engagement and support for action. The combustion of fossil fuels creates "dirty energy" and emits large amounts of health-damaging pollutants. In addition to advancing climate change, these emissions directly pollute the air and water that people rely on for good health. Highlighting the health impacts of such air pollution—and avoiding direct mentions of climate change—has been found to increase support for mitigation policies among political conservatives.[69]

Communicators may also wish to emphasize the health benefits that come from taking steps to prepare for and help prevent climate change. These benefits include more bicycle- and pedestrian-friendly communities, healthier food, reduced motor vehicle–related injuries and deaths, cleaner air and water, increased physical activity, decreased obesity and reduced morbidity and mortality associated with it, increased social capital and well-being, and lower levels of depression.[70]

should carefully consider each of the following frames and how an audience might respond to it. In some cases, research suggests a clear recommendation about which frame to use no matter what. In other cases, climate communicators need to determine which frame is likely to be most effective with their audiences on a case-by-case basis.

Loss versus Gain: Many environmental issues can be framed either positively or negatively, which can impact how an audience perceives and evaluates them. For example, highlighting the potential for climate change to threaten our way of life evokes a negative, loss frame. In contrast, many preparation-oriented messages use a gain frame when they focus attention on benefits that come from building more resilient communities and infrastructure. The negative feelings associated with losing something (such as losing $100) generally outweigh the positive feelings associated with gaining that same thing (such as winning $100). When policies and outcomes

SIDEBAR 11

Framing and the Politics of Carbon

Although many economists and climate scientists agree that a carbon tax would be the most streamlined step the United States could take to reduce its contribution to climate change, support for a carbon tax among major politicians is fairly limited. At the same time, many businesses and individuals voluntarily purchase carbon offsets (or carbon credits), which promise to balance out the greenhouse gases produced by particular activities they are engaging in, such as flying across the country. How much of this support is a reflection of the framing power of the words "tax" and "offset"? CRED researchers polled a large national sample about a program that would raise the cost of certain products believed to contribute significantly to climate change (such as air travel and electricity) and use the money to fund alternative energy and carbon capture projects. The identical program was described as a carbon tax to half the respondents and as a carbon offset to the other half. This simple change in framing had a large impact on whether people said they would buy a product with an inclusive carbon fee. When considering a pair of products, 52 percent of respondents said they would choose the more expensive product when the cost increase was labeled a carbon offset, but only 39 percent said they would choose it when the cost increase was labeled a tax. Support for regulation to make the cost increase mandatory was greater when it was labeled an offset than when it was labeled a tax.

Strikingly, the framing effect interacted with respondents' political affiliations. More liberal individuals were equally likely to support the program regardless of the label used, but more conservative individuals strongly preferred the carbon offset to the carbon tax. A follow-up study revealed that the tax label triggered many negative thoughts and associations among more conservative individuals, which in turn led them to reject the carbon tax. These findings demonstrate that communicators should carefully consider the way in which carbon regulations are labeled or presented. Communicators may wish to use politically neutral terms when describing carbon regulations, such as the label "user fee," which makes the point that those who receive a benefit should pay for it.

are framed in terms of potential losses, people are usually willing to take bigger risks to avoid those negative outcomes.[62] The reverse is also true: when policies and outcomes are framed in terms of potential gains, people become more risk averse, preferring "sure bets" or smaller, less risky choices. **Communicators can use this knowledge when deciding whether to frame a message or decision as a loss or a gain, depending on whether the goal is for people to make a risky choice (investing in certain insurance policies) or a less risky choice (line drying clothes to save energy).**

Present versus Future: People tend to perceive immediate threats as more relevant and of greater urgency than future problems.[63] Because people ***discount the future*** (thinking it will be easier to solve future problems due to an [unrealistic] technological fix or an [imagined] greater availability of financial resources), **communicators should generally try to highlight the impacts of climate change that are already being experienced in the present or are likely to occur in the very near future.** This will create an urgency to act now. Similarly, people tend to think that it will be easier to part with money if necessary in the future, as demonstrated by research that shows that employees are often willing to commit next year's pay raise to a retirement plan.[64] **In terms of a climate preparedness or energy conservation program, participation may be greater if communicators**

SIDEBAR 12

Making Clean Energy Attractive across Political Lines

One part of the solution to climate change is the widespread adoption of clean or renewable energy, such as solar power. Energy campaigns typically focus on how solar technologies reduce emissions or utility bills. These "reduce" messages are likely to be effective in motivating liberals to invest in renewable energy, as they see themselves as personally responsible for reducing their energy use and emissions. However, this language may fail to engage more politically conservative individuals who do not share this sense of obligation. Dena Gromet and CRED researcher Howard Kunreuther, both of the Wharton School at the University of Pennsylvania, have investigated how framing renewable energy as *reducing negative aspects of energy use*, as compared to *increasing positive aspects of this use*, interacts with political ideology to affect individuals' interest in adopting solar power.

In two studies of California homeowners, participants could choose to read about different home improvement options, one of which was installing solar panels on their homes.[71] The researchers varied whether the solar option was described as reducing a negative aspect of energy use ("Want to reduce your use of fossil fuels? Get solar panels!") or as increasing a positive aspect ("Want to increase your use of renewable energy? Get solar panels!"). The reduce/increase framing interacted with political ideology to predict people's decisions about whether or not to learn more about solar. Liberals were more inclined than conservatives to choose to learn about solar when a "reduce" message was used, whereas the divergence between liberals and conservatives was lessened (or reversed) when an "increase" message was used. Additional questions revealed that "reduce" messages were more appealing to liberals because they communicated that individuals had a personal obligation to conserve energy, whereas "increase" messages conveyed greater personal benefit.

These findings demonstrate that **the emphasis on reducing a negative aspect of energy use, as compared to increasing a positive aspect, can dramatically affect individuals' interest in renewable energy**. This framing effect appears to be primarily driven by how messages resonate with individuals' political views and sense of personal responsibility for addressing energy issues. **The results highlight the importance of understanding how different framings resonate with individuals' political values, which can influence their energy choices.**[1] **In addition, research suggests that highlighting benefits or gains from taking action may be an effective way to increase willingness to respond to climate change, regardless of an individual's political orientation.**[72]

[1] This research was conducted as part of the Sunshot Solar Energy Evolution and Diffusion Studies (SEEDS) program, Department of Energy.

ask people to sign up in advance to take a more cost-intensive action down the road, such as committing to weatherizing their homes the following year. It is important to note that some individuals may actually respond more positively to future-oriented information about climate change, in part because doing so can make the issue less overwhelming while giving people a sense that they can still do something.

Local versus Global: Climate change impacts and solutions can be framed as local (local extreme weather events; community-level preparedness efforts) or as distant (climate change as a global phenomenon; international agreements). **In general, communicators should frame climate change as a local issue, both in terms of consequences and possible solutions.** In part, this is because local impacts and solutions are more vivid and thus easier to think about for most people. Additionally, research has found that the more traditional approach of highlighting the global scale of the problem without also highlighting local impacts may actually increase political polarization, as such messages resonate well with liberals but poorly with conservatives.[65] **Thus communicators may wish to emphasize local impacts first, before scaling up to show how climate change is affecting other parts of the country and the world.** ■

TIPS Connect Climate Change to Issues That Matter to Your Audience

Your communication strategy should integrate frames that help audience members quickly identify why and how climate change is meaningful to them. To bolster audience engagement, use frames that speak to your audience's major concerns. Consider the following questions before determining which frames to use:

- What are your audience's major concerns and worries? Which content frames (such as a public health frame or a national security frame) would resonate most clearly with your audience?
- How can you use structure frames to make the issue relevant and meaningful to your audience?
- How can you incorporate a focus on present, local impacts into your communication strategy?
- Are there small changes you can make in how you describe climate impacts or climate solutions that would change how your audience reacts to your message?

Keep in mind that your answers to the questions in **SIDEBAR 1: Getting to Know Your Audience**, can also help you to determine the best form and content frames to use in your communication strategy.

Use Images and Stories to Make Climate Change Real

"Blah, blah, blah."

All too often, climate communicators rely on written communication and facts and figures to get their messages across. Images and storytelling, however, are critical tools for making climate impacts, solutions, and stories more real. This section describes how images can be used to underscore certain points, what types of images are most memorable, and why images of people and familiar things are usually more effective than scientific graphs. This section also provides tips on how communicators can employ storytelling to enhance their audiences' attention and engagement.

Use Images That Inspire and Empower

People think and feel using images. Images convey emotions and add emotional weight beyond what words can accomplish. Rather than directly telling the audience what to do or how to feel, images can let audiences create meaning for themselves. Although the use of images is not as well researched as other areas of climate change communication, a few studies have highlighted several important considerations that climate communicators can keep in mind when using images.

Climate change imagery often falls into one of two categories: images that increase the emotional impact or saliency of climate change, and images that increase self-efficacy and the feeling of personal agency.[73] Dramatic images that prompt fear (such as those of environmental refugees or "drowning" polar bears) or that depict climate impacts (such as aerial views of flooding) are good for attracting attention and giving climate change a sense of emotional importance. However, these types of images are less effective in the long-term because they distance people from solutions and deeper engagement. On the other hand, images that promote self-efficacy (such as images of renewable energy or insulating one's home to reduce energy use) tend to be less salient (that is, they are less effective at grabbing an audience's attention). **Communicators should take care to use both types of images, depending on whether they wish to attract audiences' attention or help empower audiences to act.**

Climate communicators may also wish to employ cultural archetypes or icons to help audiences relate to climate change more effectively. For example, the quintessence of masculinity, as represented by construction workers, first responders, or cowboys, tends to align with values that are pervasive in American culture—boldness, scale, dominance, and progress—and thus may help engage new audiences on climate change.[74] Climate communicators should also take care to use clear, realistic images that closely match the narrative of accompanying text, which can enhance readers' understanding of climate change and its implications.[75]

Show People, Not Pie Charts

In a series of experiments to find out what features make images more memorable, researchers discovered that **images of people or groups, faces, and common household items are among the most powerful.**[76] Contrary to popular belief, aesthetically pleasing scenes like landscapes, architectural exteriors, wide-angle vistas, backgrounds, and natural scenes leave less of a mark.[77]

Researchers have also found that visualizations such as bar charts, pie charts, and scatter plots (which are frequently used to communicate climate change) are among the least memorable of all images. These kinds of images require prior knowledge and skill to read effectively and thus are appropriate only when designed and chosen with an audience in mind.[78] Unique visualization types, such as those using pictorial elements, repeated small multiples (such as stick figures to represent people), grids or matrices, trees and networks, or diagrams, are easier to remember than common graph types such as pie charts, scatter plots, bar graphs, and line graphs.[79] **Moreover, the inclusion of objects, photographs, people, cartoons, and logos can help enhance memorability of visualizations used to communicate about climate change.**

Stories are among the best ways to connect with core human values and social identities, build bonds between individuals and groups, and engage the public on climate change.

Use Storytelling to Strengthen Engagement

Stories are the single most powerful tool in a leader's toolkit.
–Howard Gardner, Harvard University

According to one recent poll, eight in ten Americans do not understand what it means to study something scientifically.[80] As a result, science- and fact-based arguments about climate change are unlikely to resonate with the majority of the American public. Instead, stories are among the best ways to connect with core human values and social identities, build bonds between individuals and groups, and engage the public on climate change. This doesn't mean that facts cannot be persuasive; it's just that stories are more likely to make those facts more relevant. Stories about climate change can take a range of forms, including personal speeches, films, short stories, plays, or newspaper or magazine articles.

Stories influence people's beliefs because they shift the frames of reference for emotional and cognitive processes.[81] In addition, stories can enhance people's capacity for empathy.[82] As an alternative form of mental processing, both fictional and factual stories open people up

to new information, attitudes, intentions, beliefs, and behaviors.[83] Stories can also focus on a long and glorious past as a motivator to care about and ensure a livable future.[84]

Climate communicators may wish to ask their audiences to tell their own stories about climate change impacts and solutions. **Communicators can then share these stories with others and can create their own by identifying what drives them personally and by determining why climate change matters to others.** For more resources on storytelling, see the **FURTHER READINGS** section on Page 82.

TIPS Use Images and Stories to Make Climate Change Real

Audiences bring different knowledge and experiences to their interactions with images—especially technical images like charts and graphs. Subject matter, composition, point of view, and visual style are just some of the ways that images communicate and frame communication, and connecting with an audience is just as important for images as it is for verbal communication.

Consider the following questions as you incorporate images and storytelling into your communication strategy:

- Do your images empower and inspire your audience?
- Do your images depict people, groups, faces, or common household items rather than landscapes and vistas?
- Are you using visualizations like bar charts, pie charts, and scatter plots sparingly and with your audience's previous knowledge and skills in mind?
- Are you using realistic images that closely match the narrative of accompanying text?
- Are you employing storytelling (both real and fictional) to help make climate change more vivid and to help people imagine possible courses of action?

OVERCOMING BARRIERS:
Science, Skepticism, and Uncertainty

OVERCOMING BARRIERS: SCIENCE, SKEPTICISM, AND UNCERTAINTY

Climate change is complicated. It involves scientific jargon, numbers that are hard to comprehend, and significant amounts of risks and uncertainty. The technical language used to describe climate change—terms like "anomaly" and "positive feedback"—can mean vastly different things to the general public than they do to scientists. Moreover, the term "global warming" has confused many people, who have come to understand climate change as a universal increase in temperatures rather than a global shift in weather patterns.[85] While communicating about the science of climate change alone is often insufficient to catalyze engagement around climate change, communicators should still understand how to approach some of the basic issues surrounding science and risk communication (especially as they relate to climate change), uncertainty, and climate skepticism, which are explained in this part of the guide.

People update their mental models (usually unconsciously) by incorporating new information, correcting misinformation, and making new connections with existing knowledge.

7 Make Climate Science Meaningful

"I have no idea what those numbers mean."

Scientists rely on quantification because numbers, even when uncertain, provide a consistent language for discussing the changes they are observing in our climate system. Yet for most members of the public, these types of statements are not meaningful. In part this is because most people are not familiar with or used to thinking in these terms. Similarly, without scientific training, it can be difficult for people to judge the relative importance, meaning, and quality of particular scientific facts or statements. The result is that numbers and statistics—on their own—do not provide an anchor to ground and generate an emotional response, which is crucial for engagement and action for many people. This section describes how people understand scientific phenomena like climate change, explains how to translate scientific and numerical information into familiar terms, and identifies which metaphors can help the public better understand climate change.

Uncover How Your Audience Understands Scientific Phenomena: The Role of Mental Models

Most Americans do not have a complete understanding of climate change and its associated risks. Yet most people have at least a bit of knowledge about climate change, which they will use to interpret new information they hear about it. People's understanding of climate change is often based on a mix of associations with the phrases "global warming" or "climate change," memories of related phenomena and past experiences, analogies they've heard from others, intuitive perceptions, and relevant yet incomplete sets of facts. These form the ingredients of a ***mental model***.

Someone's mental model or ***constructed concept*** of climate change can answer some of the following questions: (1) What is climate change? (the issue and its causes); (2) If the climate changes, what might happen? (impacts); and (3) What can be done about climate change? (policy, individual action). People refer to mental models to judge the level of risk associated with a problem, its controllability, and its manageability. Mental models influence what people pay attention to, how they approach problems, and what actions they take.[86]

While a person's mental model of climate change can be flawed or contain misconceptions, it is not fixed. People update their mental models (usually unconsciously) by incorporating new information, correcting misinformation, and making new connections with existing knowledge. This presents an enormous opportunity for communicators. For new climate change insights to take hold, communicators can map the mental models that an audience already uses, create new models using facts and practices to refine or replace existing ones, and employ strategic messaging to correct wrong information and help people update their assumptions. (See **SIDEBAR 13: A Mental Model Example: Using Images to Understand How People View the Stability of the Climate System**.)

Sometimes people seek out or absorb only the information that matches their mental model, confirming what they already believe to be true. This can lead people to avoid, dismiss, or forget information that will require them to change their minds and possibly their behavior. This phenomenon, called ***confirmation bias***, poses a potential stumbling block for those who try to communicate new information and options for behavioral change. **While confirmation**

bias is difficult to overcome, communicators can make audiences aware of the phenomenon. They can ask audiences to question themselves: "Could I possibly be wrong?" and "What would be the worst thing about being wrong?" Simply making people aware of this bias and encouraging them to have an open mind can be quite effective.

SIDEBAR 13

A Mental Model Example: Using Images to Understand How People View the Stability of the Climate System

Anthony Leiserowitz, director of the Yale Project on Climate Change Communication, has examined Americans' mental models about the stability of the climate system.[90] In nationally representative polls, Leiserowitz and his colleagues asked participants to indicate which one of five different pictures best represented their understanding of how sensitive the climate system is to global warming. The researchers then compared participants' mental models to their beliefs about the existence of climate change.

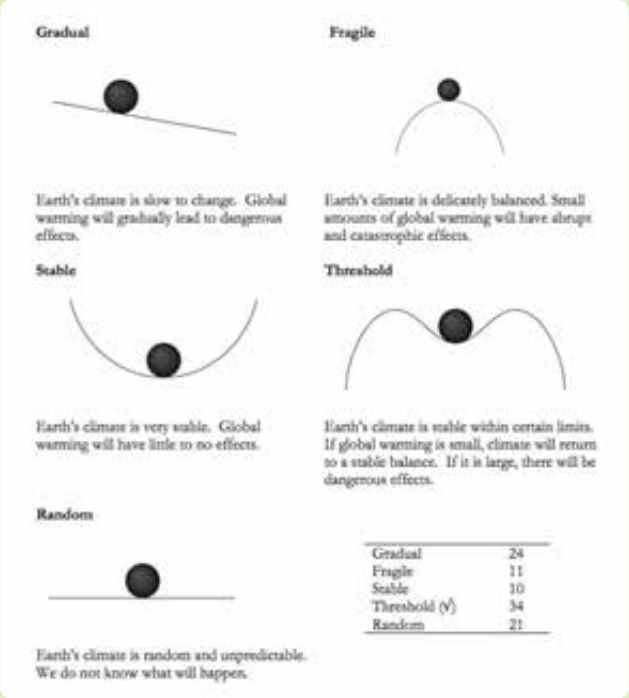


Figure 1: This image shows that people's beliefs about the stability of the climate system strongly correlate with their beliefs about whether or not climate change is happening. Image from Leiserowitz, A., Smith, N., & Marlon, J.R. (2010). *Americans' Knowledge of Climate Change*. Yale University. New Haven, CT: Yale Project on Climate Change Communication. www.environment.yale.edu/climate/files/ClimateChangeKnowledge2010.pdf.

The results were striking: people's beliefs about the stability of the climate system strongly correlated with their beliefs about whether or not climate change is happening. Those who said they believed climate change was happening were much more likely to endorse *gradual, fragile, or threshold* models of the climate system. In contrast, those who said they were skeptical of climate change overwhelmingly chose either the *random or stable* pictures. These findings point to the pervasive effects that mental models can have on people's beliefs about the role of human action in affecting the natural world. Providing audiences with a basic explanation of the stability of the climate system, in combination with other climate communication techniques discussed in this guide, may help improve people's understanding of our complex climate system.[91]

Communicate on a Human Scale

Often, the metrics and scales that scientists use to describe climate science are unfamiliar and unintuitive to most people. For example, people may think about the weight of a car when they hear a quantity measured in tons yet become confused when a volume of gas (such as CO_2) is described using the same metric, since our usual perception of gases is that they weigh nothing. When the scale or metric is confusing and doesn't translate into everyday experience, people have difficulty hearing or processing the information.

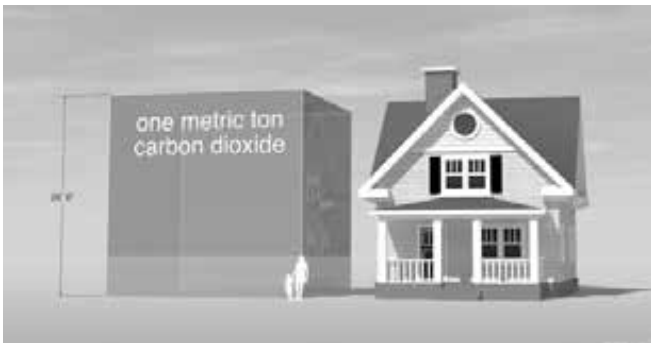


Figure 2: Visual representations of large numbers and unfamiliar concepts (such as tons of CO2) can be helpful to communicate information on a human scale. Image courtesy of Carbon Visuals (carbonvisuals.com) with funding from the Environmental Defense Fund.

SIDEBAR 14

Using Labels to Help Consumers Save Money and the Environment

The fuel economy of a vehicle can be expressed in several different ways. Fuel economy can be expressed as the amount of gas consumed, the cost in dollars to drive a certain distance, or the amount of carbon dioxide or greenhouse gases emitted. The U.S. Environmental Protection Agency and the National Highway Traffic Safety Administration recently overhauled the fuel-economy labels that appear on all new vehicles by adding additional fuel-efficiency "translations." The label still includes miles per gallon (MPG), but also includes an annual fuel cost estimate, gas consumption per 100 miles, and greenhouse gas and smog ratings. (See Figure 3, above.) With these new labels in mind, CRED researchers Adrian Camilleri and Richard Larrick conducted two studies to determine how changing metric and scale information on vehicle fuel-economy labels can help people make more informed choices. Across the two studies, Camilleri and Larrick found that consumers' fuel-efficiency decisions are strongly affected by the type and form of information provided: study participants chose fuel-efficient vehicles more often when fuel economy was expressed in terms of cost of gas over a long time-frame—100,000 miles (or roughly the life of a vehicle). This is an important finding, as current labels do not help people understand the long-term costs of owning less fuel-efficient cars or the savings realized by owning more fuel-efficient cars.

Figure 3: Studies show that consumers' fuel-efficiency decisions are strongly affected by the type and form of information provided on fuel-economy labels.

To avoid these potential pitfalls, communicators should translate unfamiliar or unintuitive statistics and numbers into relatable, easy-to-understand terms. CRED researchers (and others) have shown that using different metrics and scales to represent the same information can strongly influence people's preferences and behavior. For example, people prefer more fuel-efficient cars when information about fuel economy is presented in terms of: (1) the cost of gas rather than how much gas is consumed (different metrics); and (2) the cost savings over 100,000 miles of driving rather than over 100 or 15,000 miles (different scales).[87] This is because people quickly grasp that 100,000 miles is roughly the lifetime of a vehicle, making it easy to incorporate fuel-related costs into the up-front cost of purchasing a car.

It is also easier for people to understand numbers when the same piece of information is simultaneously presented in multiple formats.

SIDEBAR 15

Examples of Powerful Facts from Trusted Messengers

Research suggests that sticking to just one or two facts or figures, especially when they are attributed to trusted and reputable sources (especially those that don't seek profit or political gain), can be an especially effective way to bolster our understanding of climate change. Here are a few powerful facts about climate impacts and solutions that communicators can use to help build people's understanding of climate change and their support for solutions:

- According to the American Lung Association, the toxic chemicals in the air we breathe are affecting the health of nearly half of all Americans.[92]
- According to the Department of Energy, solar energy is the most abundant energy resource on Earth. The solar energy that strikes Earth is equal to more than ten thousand times the world's total energy use.[93]
- According to NASA, the ten warmest years on record were all after the year 2000.[94]
- According to the National Solar Jobs Census 2013, solar jobs in the United States are growing ten times faster than the national average.[95]
- According to the Centers for Disease Control and Prevention (CDC), health impacts from climate change and ozone pollution will result in significant increases in acute respiratory symptoms, asthma, weather-related hospital admissions for children and the elderly, and premature deaths.[96]
- According to an economic risk report jointly conducted by a leading research firm and the world's largest catastrophe-modeling company, if we continue on our current path, by 2050 between $66 billion and $106 billion worth of existing coastal property will likely be below sea level nationwide.[97]

SIDEBAR 16

Using Metaphors to Help People Understand the Science of Climate Change

Metaphors, which help translate abstract concepts into familiar terms, are an especially effective tool for science communication. **Metaphors are especially important when communicating about abstract issues like climate change because they help relate a complex issue to people's everyday life and personal experiences.** Communicators should keep in mind, however, that not all metaphors are created equal—some can actually backfire by leading the audience away from productive engagement with the issue. For example, many medical metaphors about climate change ("Earth has a fever") are easy to grasp because people have lots of personal experience with fevers and illness, but they can also confuse people because they are related to concepts that don't fit the issue well.

Using a combination of methods, the FrameWorks Institute has identified the following metaphors that can help people better understand the causes of and solutions for climate change:

***Regular versus Rampant Carbon Dioxide*:** This metaphor helps people understand why high levels of carbon dioxide are problematic. Some carbon dioxide (CO2) is needed for a lot of life processes. This is called *regular CO2. Rampant CO2*, on the other hand, occurs when we engage in actions like burning fossil fuels and driving cars, which put large amounts of CO2 into the atmosphere and oceans. This is called rampant CO2 because there is too much of it accumulating in the wrong places, causing problems for our climate. Regular CO2 will always be needed, but we need to start reducing rampant CO2.

***The Ocean as the "Heart of the Climate"*:** This metaphor helps people think about the role that oceans play in regulating the climate system. Much as the heart regulates the flow of blood throughout the body—controlling the circulation of blood and making sure the right amount gets to each part—the ocean sustains the climate system and keeps it in balance by controlling the circulation of heat and humidity. The ocean is the heart of Earth's circulatory system. It moves moisture and heat to the oceans, atmosphere, land, and other parts of the climate system.[98]

(See **SIDEBAR 14: Using Labels to Help Consumers Save Money and the Environment**.)[88] Additional research suggests that **sticking to just one or two facts or figures, especially when they are attributed to trusted and reputable sources, can be an especially effective way to bolster people's understanding of climate change.**[89] Visual representations of large numbers and unfamiliar concepts (such as tons of CO_2) can also be helpful.

Use Familiar Concepts to Help People Understand Science and Statistics

People interpret statistics and scientific facts by relating them to what they already know. Communicators should place statistical or scientific facts within a broader, familiar context so it is easy to make sense of that information and use it to make decisions. Communicators can also help people make explicit comparisons to familiar objects and concepts that

they encounter in the course of daily life (such as time or social interactions). For example, the difference between millions and billions of dollars lost to climate impacts is hard for people to grasp because both amounts sound so large. But comparing those losses to the (relatively small) amount of money being spent to combat climate change draws attention to the inequality between the huge scale of the problem and the insufficient scale of the current response. ■

SIDEBAR 17

Translation in Action

Take a look at the following statement: "In 2011, Americans experienced a record-breaking 14 weather and climate disasters that each caused between $1 billion and $10 billion in damages, in total costing approximately $53 billion."[99] This sort of statement is common in reporting on climate change. Yet on its own, this statement is unlikely to provoke a strong response or to motivate action, because $53 billion means very little to people.

Now, compare the initial sentence with the following translation: "In 2011, Americans experienced record-breaking weather and climate disasters that cost our country approximately $53 billion. That is more than eight times what our government spent on financing clean energy projects in the same year. We can either pay now or pay later to address climate change. It is our duty to responsibly and wisely manage our country's financial resources. An important way to do this is by investing in clean energy projects today that can benefit us all in the future."[100] Notice how this translation incorporates an easily understood comparison (between money spent on cleanup efforts and money spent to avoid the problem in the first place) into a message that highlights widely shared core values (responsible management of shared resources; financial prudence) and promotes a particular solution (investments in clean energy). Remember: numbers and statistics can be powerful tools for communicators, but they should not be the centerpieces of the message. Instead, numbers should be used to support a well-framed, consistent core narrative about climate change, climate impacts, and climate solutions.

TIPS Make Climate Science Meaningful

In some situations, the communication of statistical and scientific data, findings, and facts is important or unavoidable. In these cases, communicators' aim should be to provide numerical information in a way that is readily usable and interpretable by their audiences. Consider the following questions before presenting numerical and scientific information:

- Have you identified what you can and will achieve by communicating numerical information, scientific findings, or facts? Are your expectations of the effects that such information will have on audiences supported by past research on and experience with climate change communication?
- What do you want your audience to do with the information you present? Are there ways to accomplish the same goals by communicating information besides scientific facts about the climate system, such as information about climate solutions or climate impacts?
- How familiar are people with the metrics and scales you are using? Could they be confused by an unfamiliar or nonstandard use of an otherwise familiar term (such as "tons")?
- If you are using numbers or statistics to highlight the scope or severity of the problem, are you successfully incorporating metaphors and real-life comparisons to help make those numbers meaningful for people?
- Are you providing enough context for people to understand the new information?
- Are you using numbers and facts sparingly and attributing the one or two facts and figures you do use to messengers or sources your audience knows and trusts?

SIDEBAR 18

How Time Horizons Affect Our Decisions around Climate Change

One thing that makes it particularly hard to capture the public's attention about climate change is the fact that many of the most serious impacts that must be prevented may not happen for quite a while. Future events are hard for people to care about because humans naturally discount future gains. Winning $100 today feels great, but winning today and waiting one month for the payment feels much less good. When given the choice between $100 today and $120 one month from now, many people will take the smaller reward today rather than waiting a little longer for much more. That future $120 is mentally discounted—enough to feel less valuable than $100 now.[101] CRED researchers David Hardisty and Elke Weber have found that the same attitude also influences people's decisions when it comes to protecting the environment.[101]

A similar effect happens when it comes to losses, such as incurring a loss now or in the future.[103] When scientists tell the public that sea levels will rise by several feet in the coming century, people's natural tendency to discount, combined with a long time scale, can make the predicted rise seem inconsequential. Even with more easily imaginable outcomes such as economic losses of large magnitude, this discount effect is strong enough to make the costs of a $300 million levy project (today) feel about the same as a $1.3 billion flood-cleanup effort ten years later because people often delay large losses, even if delaying the action will result in higher costs than paying in the present. This may help explain why many people are not motivated to invest in flood-prevention efforts despite the fact that mitigation efforts cost much less than recovery on average.[104] A contribution of $1,000 to mitigation efforts is less than $4,000 in recovery costs, but the $4,000 may be discounted just enough to make it feel like less of a hit than the immediate $1,000. Because of this, climate communicators may do better to place emphasis on the pure costs of cleanup and to de-emphasize the fact that cleanup will take place sometime in the future.

TABLE 3

Words with Different Meanings to Scientists and the General Public

The following table lists many words that scientists use to describe and talk about climate change, yet that mean different things to the general public, journalists, and policy makers. Make sure to avoid jargon and use words that truly convey what is meant to be communicated.

Scientific Word	Nonscientific Meaning	Better Language
enhance	improve	intensify, increase
uncertainty	not knowing	range
risk	low-probability event	probability
error	wrong or incorrect information	uncertainty associated with a measuring device or model
bias	unfair and deliberate distortion	offset from the observed value
positive trend	good trend	upward trend
theory	hunch, opinion, conjecture, speculation	physical understanding of how this works
hypothesis	conjecture	framework for physical understanding
sign	indication	positive/negative value, plus/minus sign
values	ethics, money	numbers, quantity
manipulation	exploitation	changes in experimental or model conditions to study the impact of those conditions
scheme	conspiracy	blueprint
anomaly	abnormal occurrence	deviation from a long-term average
mitigation	fixing something after it breaks	avoiding or preventing further climate change and global warming
adaptation	“going with the flow”; dealing with problems as they arise	increasing preparedness before impacts occur; preparing for climate impacts that are already happening
geoengineering	Frankenstein-type messing with nature	deliberate alteration of natural Earth systems
environment		the air we breathe and the water we drink

8 Acknowledge Uncertainty, But Show What You Know

"If the scientists aren't 100 percent sure, why should I listen to them?"

There's no escaping it: communicating on climate change involves talking about uncertainty. Uncertainty exists in part because climate science is complex and the climate system is even more so. While it may be tempting, communicators should not ignore the uncertainties that climate change presents, be they uncertainties associated with timing and severity of impacts or uncertainties related to the success or failure of mitigation and adaptation strategies or technologies. Communicators should be aware that even small levels of uncertainty are often used strategically to oppose climate action. This section explains how climate communicators should focus on what is known, describes which uncertainties matter and which ones don't, and explains how to help audiences become engaged on climate change, even when uncertainties do exist.

Uncertainty on its own is not necessarily a barrier to engagement or action. Rather, it is the implied and perceived implications of uncertainties that can make engagement challenging.

The Role of Uncertainty in Climate Change Communication

At its core, human decision making deals with uncertainty. While people may be uncomfortable when confronted with uncertain situations or information, they are also experts at taking action under such conditions. Take the example of the daily weather forecast. Despite the fact that people tend to misinterpret probabilities and percentages, many people have little trouble translating a 60 percent chance of rain into concrete action (such as taking an umbrella). More importantly for communicators, most Americans now perceive and know that there are real scientific and political uncertainties surrounding climate change. As a result, communicators may need to recognize these uncertainties. **In fact, research suggests that acknowledging uncertainty at the beginning of a climate communication message can increase people's willingness to engage with the issue.**[105] The question is how to engage with uncertainty more broadly in a way that helps people understand and respond to the issue rather than turns them away.

Uncertainty on its own is not necessarily a barrier to engagement or action. Rather, it is the implied and perceived implications of uncertainties that can make engagement challenging. **If people believe that scientific or political uncertainty means that the problem is too difficult**

to solve, they will be unlikely to support action. Conversely, if people are able to understand the ways in which uncertainty can provide opportunities for a new and better future, they are likely to embrace the issue and proposed solutions. Ultimately, it will likely be people's experiences with emerging solutions and policies to address climate change that will narrow the gap between expert and public perceptions of the issue, rather than people's exposure to information about the uncertainties.[106]

Focus on What Is Known

Communicators should generally aim to highlight the facts about climate change that are known with relative certainty. This is especially true of the fact that there is overwhelming consensus among climate experts regarding the basic facts of climate change. Despite this, many Americans

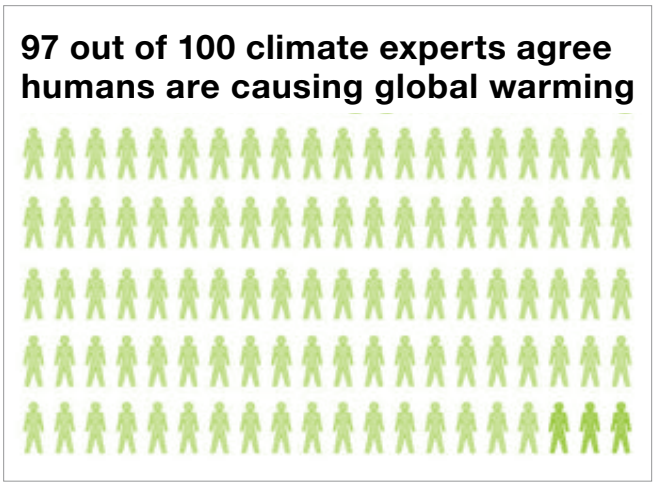


Figure 4: This image provides a clear visual example of the overwhelming scientific consensus on climate change. Image from Cook, J., & Lewandowsky, S. (2011). *The Debunking Handbook*. St. Lucia, Australia: University of Queensland.

SIDEBAR 19

African Farmers and Climate Information

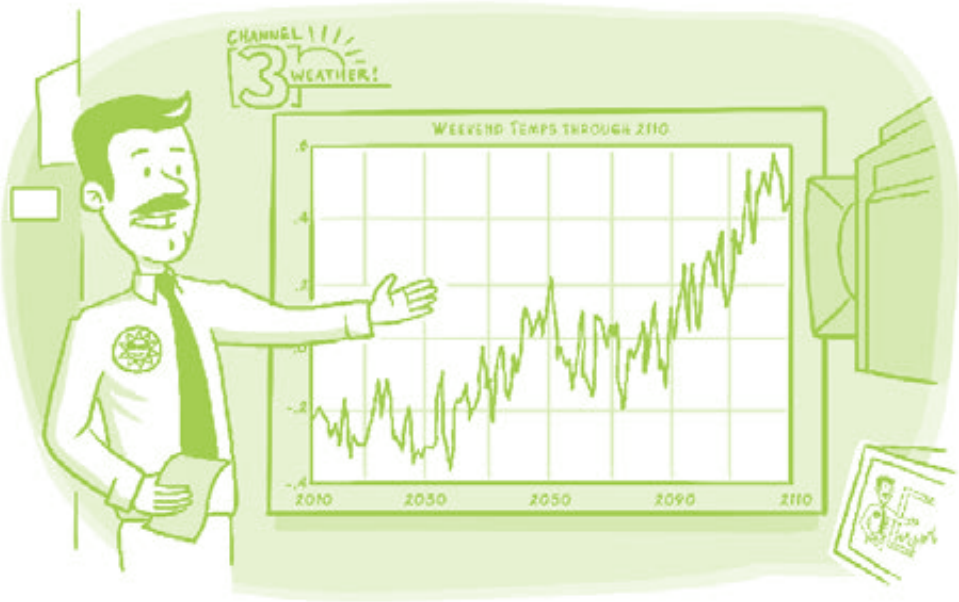
Over the last decade, CRED researchers have been studying participatory processes in a variety of cases to understand how these can affect the use of climate information more broadly. In Uganda, discussion within farmers' groups facilitated the understanding of probabilistic seasonal rainfall forecasts by allowing members to pool their ideas and to plan appropriate responses.[114] This resulted in greater use of forecasts in agricultural decisions by group members, compared with farmers who did not participate in the group discussions. Farmers in Argentina also found value in group discussions of forecasts and other topics to improve their farming. Dairy farmers in the Dominican Republic used participatory meetings to explore the introduction of insurance mechanisms and were able to change the contracts offered to reflect their needs. **Participatory processes have an important impact on decision making and can be valuable for sharing information or preferences, particularly** in settings that have traditionally lacked equal access to information and that are often shaped by the strategic use of uncertainty. In Burkina Faso and Brazil, participation in water user committees has contributed to reducing conflicts over water allocation and enabling greater access to political processes or authorities.[115] In all of these cases, group context eased the problems commonly found in understanding and using uncertainty.

SIDEBAR 20

Better Safe Than Sorry: Invoking the Precautionary Principle

Uncertainty is often used as a justification for inaction or business-as-usual policies. Yet communicators can and should use uncertainty to encourage people to develop contingency plans and to adopt adaptive management strategies. **Highlighting the concept of "better safe than sorry" (also known as the precautionary principle) can help individuals and communities reframe a potentially paralyzing uncertainty into justification for strong, protective action.** Former governor of California Arnold Schwarzenegger referred to the precautionary principle when he said, "If ninety-eight doctors say my son is ill and needs medication and two say 'No, he doesn't, he's fine,' I will go with the ninety-eight. It's common sense—the same with climate change. We go with the majority…the key thing now is that since we know this industrial age has created it, let's get our act together and do everything we can to roll it back."

continue to perceive a lack of scientific consensus, which researchers have identified as a major barrier to greater public engagement with the issue.[107] **Research shows that short, simple statements are some of the most effective ways to increase public understanding about the scientific consensus on climate change.**[108] Using simple, audience-appropriate pie charts can also enhance understanding of the scientific consensus on climate change, especially among Republicans.[109] **Highlighting potential**



"So yes, Dan and Kathy, as you can see it looks like it'll be up and down until 2109, but you're certainly going to want to think about abandoning the planet after that…"

solutions that involve relatively little uncertainty should also be a goal of climate communicators. The 2014 National Climate Assessment and the Intergovernmental Panel on Climate Change's Fifth Assessment Report (AR5) provide detailed guidance about what is known with relative certainty and which prevention and preparedness approaches are viable as solutions pathways.[110] See **TABLE 2: Climate Solutions and Mechanisms to Facilitate Them** for more information about solutions.

Uncover How Your Audience Responds to Uncertainty

Communicators should assume that every audience they interact with is uncomfortable with uncertainty. If communicators are presenting to a live audience, they can ask a few questions to test people's understanding of uncertainty by show of hands. For example, communicators may ask a question like, "Does a 30 percent chance of rain tomorrow mean that it will rain in 30 percent of the area, that it will rain 30 percent of the time, or that it normally rains on 30 percent of days with these conditions?" Communicators may also wish to ask questions like, "Would you base any decisions on a 50/50 chance of something occurring?" and "How likely do you think it is that an earthquake will occur in New York City in the next twenty years?" **Recognizing how an audience approaches probability, statistics, and uncertainty can help communicators tailor their communication strategies accordingly.**

Determine Which Uncertainties Matter

It is important to recognize that there are multiple sources and types of uncertainty surrounding climate change. People do not respond to all of these

SIDEBAR 21

Helping People Imagine the Future

Research from various fields is converging on a key insight for climate communicators: helping people imagine a range of possible future scenarios can support engagement. In one recent study, researchers presented participants with one of three messages about future sea level rise:

- Scientists' best estimate is 3 feet of sea level rise by 2100.
- Scientists' best estimate is 3 feet of sea level rise by 2100, but it could be as much as 6 feet.
- Scientists' best estimate is 3 feet of sea level rise by 2100, but it could be as much as 6 feet or as little as 1 foot.

In all cases, estimates of sea level rise were accompanied with a projection of how many millions of Americans would be displaced from their homes and businesses by a given level of change. Strikingly, audiences' level of support for adaptation policies was strongest when they got the message with the full range of future impacts (best guess, worst case, best case).[112] Moreover, people who received the third message also showed the biggest increases in trust in scientists, a critical predictor of belief about the reality and seriousness of climate change.[113] **This and other research points to the importance of providing audiences with a range of "alternative futures," as doing so can both increase trust in communicators and make various trade-offs and decisions more concrete.**

uncertainties in the same way. For example, there is uncertainty about the severity and timing of future negative impacts from climate change (such as storms, droughts, or extreme temperatures), scientists are not sure just what volume of greenhouse gases can be emitted before the planet reaches a "tipping point," and there is always uncertainty regarding what exactly humans will decide to do about the problem (and when they'll take action).

Columbia University researchers Scott Barrett and Astrid Dannenberg have found that people working in groups find it very difficult to coordinate their actions to avoid bad outcomes (for example, incurring financial losses) when there is too much uncertainty about exactly how much up-front action the group must take to reduce the risk. When uncertainty around such "thresholds" is too high, people stop cooperating, leading to worse group outcomes. On the other hand, Barrett and Dannenberg have also found that groups are less strongly influenced by uncertainty regarding the severity of the impact, which is good news for climate communicators.[111]

SIDEBAR 22

Strategies for Communicating Uncertainty

Practitioners can do a number of things to communicate uncertain information more effectively and meaningfully, including:

- Encourage group discussion about climate information. Work by CRED researchers in Africa and elsewhere has found that people are better able to use information involving probabilities and likelihoods to inform decision making when they process that information in a group setting rather than as individuals.[116]
- Communicate scientific information using multiple labels. People have an easier time understanding and using information when communicators use both numerical ("90 percent") and verbal ("very likely") labels and avoid negatively worded terms such as "unlikely."[117] Using only verbal labels, as is often the case both in technical (for example, the Intergovernmental Panel on Climate Change) and media discussions of climate change, leads to confusion and produces a gap between experts' understanding of uncertainty and the public's perceptions.[118]
- Whenever possible, provide clear visualizations to show data and to illustrate what is known and what is less certain. For example, graphics that use icon-based representations can quickly and easily convey degrees of consensus, uncertainty, and relationships between variables.
- When referring to uncertain events such as future storms, focus on what will happen when the next climate change–related event occurs, not on the probability of it occurring this month or this year. Doing so will motivate people to consider all future possibilities and how they want to respond, despite uncertainty around the exact timing of events.

TIPS Acknowledge Uncertainty, but Show What You Know

Given that uncertainty will always be present in climate change, communicators need to find effective ways to confront uncertainties head-on. Although communicators may worry that talking openly about uncertainty will allow audiences to slip into wishful thinking about the severity of the problem, research on the communication of uncertainty tells a different story. A growing body of empirical evidence points to the benefits of highlighting certain types of uncertainty while guiding people toward factually correct explanations where they exist. When thinking about how to communicate uncertainty, consider the following questions:

- What scientific uncertainties has your audience likely heard about?
- Are you using multiple presentation formats (for example, numerical, verbal, and visual) to communicate any given piece of scientific information?
- Are you using short, simple statements or pie charts to show that the overwhelming majority of scientists believe that climate change is real and human-caused?
- How can you highlight the opportunities that uncertainty presents to shape the future?
- Are you providing enough context when communicating uncertainty to avoid causing feelings of hopelessness, despair, fatalism, and inefficacy?
- Are you using group discussion settings where possible to help your audience engage productively with the uncertainties that exist?
- Are you using the precautionary principle ("better safe than sorry") when appropriate?

9 Approach Skepticism Carefully

"But I heard…"

One of the biggest challenges for climate communicators is correcting misinformation about the causes and existence of climate change. Just as people's preexisting mental models must be taken into account when designing communication strategies, so too must communicators know how to respond to climate change skepticism and guide people toward personally meaningful and readily usable information. People are skeptical of climate change and the need for action for a variety of reasons. This section explains why some people are skeptical about climate change, describes how to distinguish between different types and sources of skepticism, and shows how to guide people toward solutions.

In some cases, individuals' denial of climate change is also a result of more basic psychological processes that shape how people engage with information about climate change.

Why Do Some People Doubt Climate Change?

There are several types of climate change skepticism. Skepticism that stems from learning about the scientific uncertainties that truly exist in the context of the climate system is valid and an important part of the dialogue to address climate change. In contrast, skepticism that is the result of highly organized efforts by some individuals and organizations to intentionally mislead the public and policy makers (to derail efforts to confront climate change) does not play a productive role in shaping a collective response to climate change and must be addressed by communicators. In some cases, individuals' denial of climate change is also a result of more basic psychological processes that shape how people engage with information about climate change. These three main types of skepticism are described here in more detail:

Skepticism That's Part of the Scientific Process: Scientists use the scientific method to prove or disprove scientific theories and claims about how the world works. Such scientific skepticism is conducted in good faith and is a key component of the climate change research process because it allows scientists to talk about the uncertainties that still exist (for example, the exact timing or severity of future impacts) and ways to research them. Sometimes the public mistakenly takes scientific uncertainty to mean that the core principles of climate change are not settled or that no action can be taken to address it (neither of which is true). Communicators should reinforce that this type of good-faith skepticism is healthy and an important part of the scientific dialogue, at the

same time reiterating that the core science about climate change is settled and agreed upon by the vast majority of climate scientists.

Skepticism Based on Misinformation: Particularly in the United States, some groups have worked to instill doubt and climate change denial among both high-level decision makers and the general public. This has been accomplished in part by producing and distributing incorrect information about the existence and causes of climate change, supporting and promoting scientists who deny observational data about the current climate system (such as global average temperatures), and undermining mainstream climate scientists' reputations. Some of this incorrect information has been passed along to the public through the media. This false information typically frames climate change as "uncertain" and uses the uncertainty to justify delays in action. The uncertainty is emphasized by questioning isolated pieces of evidence, emphasizing the need to delay action until the science is definitive, and stating that the fixes for climate change are expensive. Bringing awareness to these types of denial efforts and their characteristics can help audiences recognize when they are being exposed to good-faith skepticism or false information.

Skepticism Due to Underlying Psychological Processes: Most people prefer to avoid negative emotions when possible. Yet the scope of climate change (and the messages climate communicators have often used) can easily lead people to feelings of sadness, fear, guilt, and hopelessness. This is particularly the case if people perceive themselves and their communities as unable to meaningfully confront the problem. One response is to avert these feelings altogether by denying the existence or downplaying the severity of climate change.[119] Through a set of mostly unconscious processes that social scientists call ***motivated reasoning***, many people perform

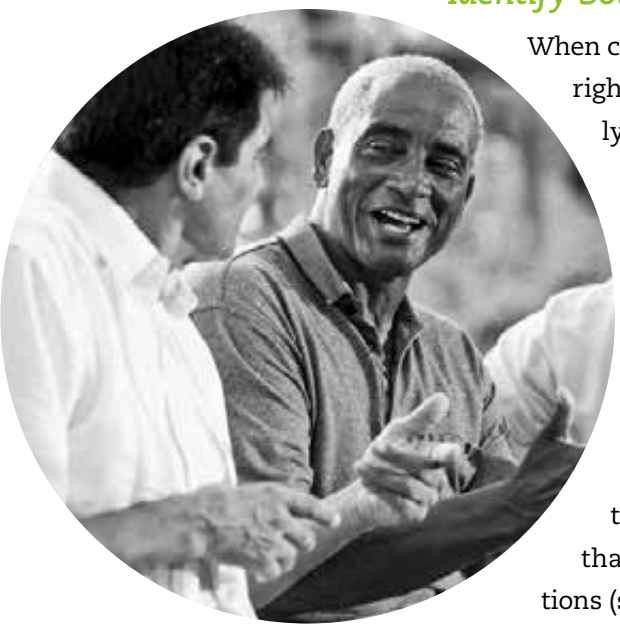
"mental acrobatics" to avoid believing that climate change is a problem or that it requires a large-scale response. Being skeptical about climate change is one way to avoid negative feelings about the issue as well as to justify inaction, and it is particularly likely to occur when proposed solutions (such as greater governmental regulation of the energy sector) are perceived as affronts to one's core identities, worldviews, and values.[120]

These mechanisms are not mutually exclusive. To some extent, they are all relevant because people have been exposed to information that highlights scientific uncertainties and disagreements among experts (real or not), as well as the cost and difficulty of responding to the issue.

Crucial to all discussions of climate change is therefore trust in scientists. Because most people are neither climate scientists nor highly science literate, people must rely on scientists and others for information about climate change.[121] Thus beliefs about an abstract scientific issue such as climate change are influenced by the extent to which people trust scientists and science to accurately and

honestly report what's happening in the world. That said, climate scientists are generally a highly trusted source of information for Americans.[122] It is important for scientists to gain the trust of the audience when acting as climate communicators. One way to do this is by showing that they too are community members, with similar concerns and life challenges as audience members. If the communicator is a non-scientist, it is important for him or her to reinforce that information about the existence and nature of climate change comes from trusted science.

Identify Sources of Doubt



When communicators encounter skepticism, doubt, or outright denial, it is important that they identify the underlying sources and mechanisms at play. **Someone who questions climate change because he or she has been exposed to false information may need to be made aware that false information campaigns are going on and that they do not represent accurate science.** In contrast, those who are skeptical about climate change because of deeper psychological processes inherent in ideology or worldview-driven motivated reasoning may need to be shown that there are solutions to the problem that are in fact in line with their deeply held convictions (see **SECTION 3: Emphasize Solutions and Benefits**) before they can accept or respond to climate change.[123]

The More Facts the Better? Not Quite

Communicators should take a multi-pronged approach to dealing with doubt and denial. The commonly held beliefs that "facts will save the day" and "the more facts people hear the better" are—as many scientists and advocates have discovered—simply not accurate. Similarly, the commonly used strategy of stating a myth (such as, "there has been no warming for the past ten years") and then refuting it with extensive evidence not only often fails to dislodge the myth but actually may reinforce it.

Climate communication researchers John Cook and Stephan Lewandowsky explain how this can happen via two effects, which they refer to as the familiarity effect and the overkill effect. The ***familiarity effect*** occurs when people hear a myth over and over again (often repeated by climate advocates in their attempts to discredit the myth), making it more familiar

SIDEBAR 23

"I Heard There's Been No Warming for Ten Years": Debunking Climate Myths

Climate change communicators often encounter the same few false claims and myths repeated over and over by climate deniers: "Climate has changed before," "There is no consensus," "It's natural," "Models are unreliable," "The temperature record is unreliable." Besides being incorrect and/or irrelevant, what these and other commonly used climate myths share is the ability to distract both honest communicators and uninformed audiences from grappling with the truly complex nature of the issue.

One claim that can be particularly confusing for audiences is the myth that there hasn't been any warming of the globe in the past ten years. This is a topic many scientists are currently studying because it involves complex research about short-term fluctuations in our climate system, but people who deny climate change often use this scientific dialogue as a blanket statement to "prove" that climate change is not real. When such claims are made (for example, in town hall meetings or other settings in which communicators can respond immediately), communicators should do the following:

1. State that the claim is a myth and therefore wrong, unequivocally, and explain in a short sentence why the talking point is false.
2. Provide some context. For example: "Organizations that deny climate change is happening cherry-pick the data and ignore information that doesn't fit their story."
3. State the core fact that you want to communicate, for example: "Climate change refers to long-term trends, and the data we have indicate an increase in global temperatures in recent decades, which is the short term."
4. Try to reinforce the core fact or takeaway with a little bit of additional detail and/or a clear graphic if possible, for example: "Using many different ways to track long-term trends, scientists have consistently found that Earth continues to warm." When possible, attribute the fact to a reputable source that the audience is likely to trust.
5. If appropriate, show people why responding to climate change makes sense, even if climate change were not human-caused. In other words, help the audience question why people would make a lose-lose wager when they can have a win-win by moving to clean energy sources that will have other positive effects in addition to climate change mitigation. For example, climate communicators may want to use a message such as, "We can gamble that our changing weather patterns are just a natural cycle that we can't do anything about. But why play Russian roulette with our kids' future when the alternative is to invest in new clean energy technologies like wind and solar power that will rebuild our manufacturing base, create jobs, and get our economy growing again?"[128]

and thus easier to believe as truth. The ***overkill effect*** occurs when communicators try to provide too many counterarguments to refute a myth, making it harder for people to cognitively grasp the complex truth relative to the simplistic myth.[124]

To avoid these negative outcomes, **communicators should lead with the core concept they want people to grasp and use only a *few* of the clearest, most important facts**, preferably from trusted and reputable sources. Contrary to some scientists' and communicators' beliefs about the public, **people *are* often open to considering new evidence and information. However, this is more likely to happen and to be effective when messages:**

- Contain one or two powerful facts or quotes from a trusted and credible source (see **SIDEBAR 15: Examples of Powerful Facts from Trusted Messengers**)
- Are presented in a compelling way (often using visualizations, pie charts, infographics, or animation)
- Start with the correct information and discuss the myth or misinformation only later on
- Connect the new fact directly to things people already care about (as discussed in **SECTION 1: Put Yourself in Your Audience's Shoes** and **SECTION 5: Connect Climate Change to Issues That Matter to Your Audience**)

- Avoid raising people's defenses, which happens when information contradicts worldviews and identities, causes negative emotions, or makes people feel that the problem is too big to solve
- Provide alternative explanations that fill in gaps in people's understanding when a belief is exposed as myth
- Announce to people in advance whenever false information is going to be discussed and debunked

Focus on Solutions, Not Just the Problem

Replacing myths and misinformation with evidence-based information and facts may help shift public opinion on climate change. Yet doing so is likely to be ineffective unless communicators also (1) address people's feelings that they are powerless to do anything about the issue and (2) acknowledge other underlying emotions about the issue.[125] In fact, a sense of paralysis and inability to confront the issue may *increase* as people better understand and appreciate the scope of the problem (often as the result of communication efforts).[126] To avoid these problems, **communicators should focus heavily on what can and already is being done to limit the impacts of climate change (for example, through climate solutions), both by individuals and collectively, as discussed in SECTION 3: Emphasize Solutions and Benefits. Strategies that fail to do so are likely to be counterproductive in the long term because they encourage people to avoid thinking and talking about the issue.**[127]

TIPS Approach Skepticism Carefully

Climate change is hard enough for most people to understand without the presence of misinformation about the issue. Consider the following questions when confronting myths, misinformation, and skepticism:

- Have you identified the sources of doubt or types of skepticism expressed by your audience?
- When addressing a myth, have you included all three of the following components: core facts, explicit warnings, and alternative explanations?
- Do you know which myths or pieces of misinformation are important to address and which ones are less critical to accomplishing your communication and engagement goals?
- Are you focusing on solutions, not just the problem?
- Are you avoiding the tendency to lead with the myth rather than with new, personally relevant information?

TAKING IT TO THE NEXT LEVEL:
Creating the Conditions for Change

TAKING IT TO THE NEXT LEVEL: CREATING THE CONDITIONS FOR CHANGE

By now, communicators should have a solid understanding of how to craft climate change messages that will improve audiences' understanding of and engagement with the issue. For communicators who want to take it to the next level, however, this section provides information, tips, and recommendations about a related challenge: translating understanding and concern about the issue into actual action. This section outlines some of the primary tools that can help communicators create meaningful and lasting behavior change.

When people set specific goals for action, and when they make these goals public, they are more likely to follow through and take action.

10 Make Behavior Change Easy

"It's too hard to do anything about climate change."

The ultimate aim of many climate change communication efforts is to encourage decision making that will help prevent further climate change and help communities prepare for climate impacts. Such changes can be achieved through multiple routes, including increasing public support for new policies and regulation, directly persuading people to change their behavior, and changing the decision-making environment to make positive action easier and more automatic. Many climate change communicators focus on the first two approaches, but the third can also offer promising opportunities. This section reviews a variety of behavioral science strategies from a range of fields (such as behavioral economics and social psychology) that climate communicators and other individuals can use to enhance audience members' likelihood of making climate-friendly choices in their everyday lives, from household energy use to transportation decisions.

Enable People to Set Specific Targets for Their Behavior

The short- and long-term goals that people set for themselves shape the information they seek out and the behavior they engage in. When people set specific goals for action, *and* when they make these goals public, they are more likely to follow through and take action. Goal setting is often

used to encourage energy conservation, such as by giving households energy-savings targets to strive for. A goal can be set by an individual or by an external entity; research suggests that both can be effective in reducing energy use.[129] **Thus communicators should provide people with opportunities to publicly set targets for their behavior or publicly commit to following existing targets, whether around household energy use, food choices, or transportation choices.**

Make Climate-Friendly Choices the Default Option

The ***default effect*** refers to people's tendency to stick with the option, choice, or behavior that is preselected for them or selected automatically. Defaults are omnipresent in modern life, which means there are many opportunities to promote positive behavior change by optimizing opt-in an opt-out choices. **Communicators can make climate-friendly behavior easier for people by presenting the climate-friendly option as the default.** For example, when people are automatically enrolled in their electric utility's "green energy" program, they are more likely to stick with the cleaner energy source than if they have to actively opt in to the green program.[130] When communicators are in a position to present people with information about various options (such as energy-saving activities or environmental policies), presenting more sustainable choices as the default can increase the likelihood that people will make the climate-friendly choice. For more information on using defaults to encourage climate-friendly behavior, see **SIDEBAR 24: Encouraging Climate-Friendly Diets through Defaults**.

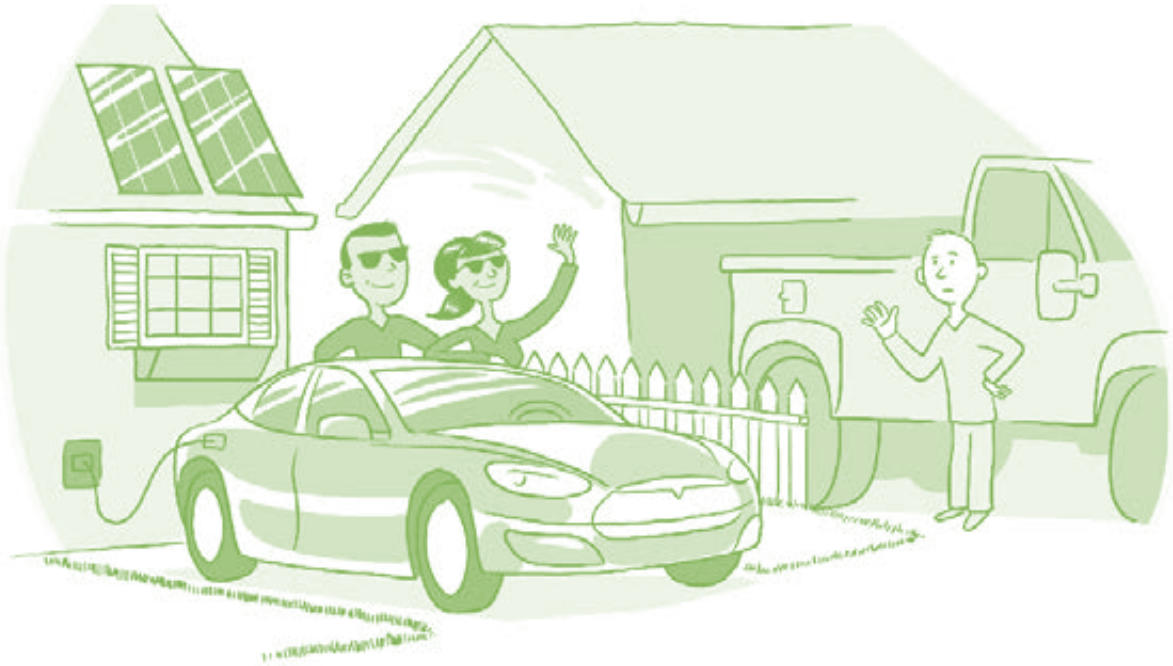
Highlight the "Green Joneses"

Humans are highly social creatures, which is why shared identities and social goals can be such powerful sources of engagement, as discussed in **SECTION 2: Channel the Power of Groups**. Another

SIDEBAR 24

Encouraging Climate-Friendly Diets through Defaults

Small changes in people's eating habits can have a significant effect on greenhouse gas emissions. Replacing meat consumption with vegetarian options can reduce individuals' contribution to climate change. However, attempts to persuade people directly to eat less meat are often unsuccessful. Setting vegetarian meals as the default option, on the other hand, can be an effective way to shift behavior. Researchers did just this in a recent study. Working with the organizers of the Behavior, Energy and Climate Change conference, researcher Karen Ehrhardt-Martinez and her colleagues noticed that the default meal choice for conference participants had always been meat-based. Participants could order a vegetarian meal if they wanted to but had to make an extra effort to do so (namely, asking for a meat-free exception on the conference registration form). For the 2009 conference, Ehrhardt-Martinez simply changed the default to the vegetarian meal (and asked carnivores to indicate they preferred meat instead, by checking a box at the time of registration). With that simple flip, consumption of vegetarian meals went from the usual 20 percent to 80 percent, which reduced carbon emissions while maintaining participants' freedom to choose the meals they wanted.[137]



by-product of humans' innate social tendencies is the influence of ***social norms*** on people's behavior. When people are made aware of what is customary behavior in a group, they often change their own behavior to match. **Communicators can help facilitate behavior change by highlighting norms surrounding climate-friendly behavior, when they exist.** The flip side is also true: communicators should be very careful *not* to play up negative social norms (for example, highlighting the large amounts of energy people are using), as doing so can actually backfire by making such behaviors seem normal and socially approved. The power of social norms to promote climate-friendly actions is described further in **SIDEBAR 25: The Power of Social Norms: Opower and Energy Bills.**

Give People Fewer Choices, Not More

Many of us are taught that the more choices people are provided, the better and the more motivated people will be. Yet research indicates that giving people more choices doesn't always lead to better outcomes. For example, in one study, grocery store shoppers visited a booth with either six jams or thirty jams on display. The results were striking. Shoppers were more likely to buy a jam when they were presented with six options rather than thirty.[131] Similar results were found in a study of employees' decisions about whether to invest in 401(k) retirement savings plans. Participation in 401(k) plans dropped when employees were offered ten or more investment options compared to participation rates in plans offering a handful

of funds. Too much choice can be paralyzing.[132] **This research suggests that communicators should limit the number of choices or options they give people to maximize the likelihood of follow-through.** For example, a home energy-savings program might provide customers with just three tips for what they can do to save energy, rather than ten or twelve, to increase the chance that customers will actually act on these tips.

Incentivize Behavior with Appropriate Rewards

Providing incentives and rewards—financial rewards, social recognition, points, or something else—is another strategy communicators can use to make behavior change easier. The key is finding the right type and magnitude of incentive for a given situation and behavior. For example, providing a financial incentive at the time a decision is made can be effective for encouraging long-term capital investments (such as purchasing energy-efficient appliances or weatherizing one's home), which often have large up-front costs and long payback periods. On the other hand, psychological research has found that monetary rewards can also have negative side effects by removing people's intrinsic motivation to act, which can decrease the likelihood of people continuing to engage in a desired behavior over time.[133]

SIDEBAR 25

The Power of Social Norms: Opower and Energy Bills

Social psychologist Robert Cialdini's groundbreaking research into the power of social norms provides a powerful tool for encouraging positive behavior change. Inspired by Cialdini's work, the energy-efficiency software company Opower teamed up in 2007 with electrical utilities in the United States to provide customers with information about how their energy consumption compared to that of their neighbors. Using simple verbal and visual messages that revealed and reinforced neighborhood social norms surrounding electricity use, Opower and its partners were able to decrease energy usage between 1.5 and 3.5 percent on average. Now working with partners worldwide, Opower continues to successfully harness the power of social norms to bring about major reductions in residential energy consumption across the world. Communicators can use the work by Cialdini, Opower, and others as a model for creating norm-reinforcing messages that shift people in a positive direction on energy savings.

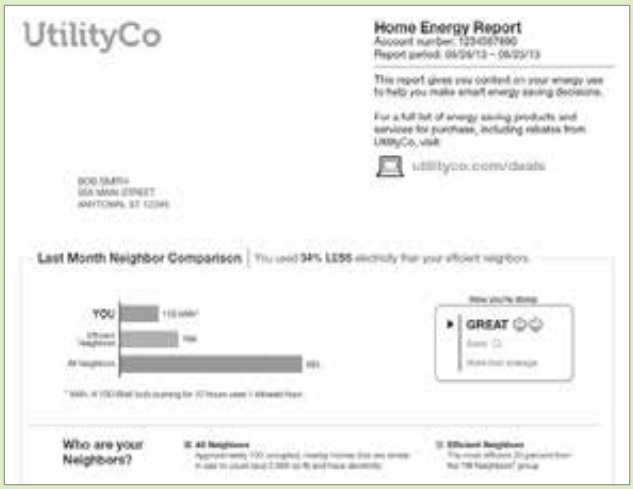


Figure 5: To yield energy-use reductions, Opower bills provide customers with information about how their energy consumption compares to that of their neighbors. Image courtesy of Opower.

SIDEBAR 26

Helping People Understand Which Actions Have the Largest Impact

Research by CRED researcher Shazheen Attari finds that communicators have an important role to play in helping people identify the behaviors that will have the biggest impact in reducing climate change. In her research with American adults, Attari found a significant gap between people's beliefs about which energy-use behaviors have the biggest impact and the actual impact of those behaviors.[138] For example, people tend to underestimate how much energy could be saved by switching to more efficient appliances and overestimate how much energy could be saved by changing to CFLs. Because people are prone to the single-action bias (feeling that they have done their part by taking a single action to confront a problem), it is critical that climate communicators work to correct misconceptions about which actions have the biggest impact in reducing climate change.[139] For example, communicators may wish to provide audience members with a list of climate-friendly choices they can make in their everyday lives, ordered from largest to smallest impact.

One alternative to providing financial rewards is to provide *social rewards* in group or public settings. This can include giving points for taking positive steps (such as reducing office energy consumption), publicly recognizing individuals' good deeds, or providing encouragement to people who take leadership roles in promoting climate-friendly actions. Another form of social reward is "gamification," which involves using game mechanics (such as incorporating rewards) to motivate people to achieve their goals. Rewards can be given online or offline and can be as simple as the posting of an individual's photo or the announcement of names of people who have made a certain commitment. **For example, when presenting to a school or community group, communicators might consider publicly sharing the names of people who have engaged in climate-friendly behaviors. This provides an immediate social incentive for action, as people are**

often highly motivated to follow the behavior of their peers, especially those they know and trust. Combining gamification with social media such as Facebook can provide additional opportunities for larger-scale sharing of one's actions and tracking progress, as well as inspiring others to join in. Mindbloom's Life Game is a good example of a game platform, combined with social media, that helps people "grow the life" they want.[134]

In addition, research conducted by CRED shows that when people are publicly given rewards for a behavior, they become more motivated to contribute to the common good. To test the combined effect of monetary versus nonmonetary (social) rewards *and* providing feedback privately versus publicly, the researchers measured and rewarded employees for contributions to their companies' energy-conservation efforts. As expected, nonmonetary (social) rewards (such as telling people they did well or that they got a higher score than average) were more motivating than receiving money for the same behavior, and employees continued their energy-saving behavior even after the incentives ended. In addition, public feedback led to more energy conservation than privately shared feedback. Most importantly, **researchers saw the greatest reduction of energy consumption when social, nonmonetary rewards were combined with public announcements. Interestingly, financial rewards in combination with private feedback didn't work at all as a motivator to save energy.**[135] **Psychologically, social rewards and receiving public feedback spur social (and pro-environmental) behavior through the activation of social norms. Additionally, public feedback may also stimulate people to communicate about their scores and may lead to more social interaction about energy conservation.**

The positive effects of social rewards and public feedback may even spill over into other parts of people's lives beyond the original behavior.[136] When promoting positive engagement through group affiliation and social identities, communicators should include social rewards for cooperative behavior and should provide rewards in such a manner that everyone in the group is aware of them (for example, by using social media platforms to share people's successes widely and in real time).

SIDEBAR 27

Goal Setting in Action: Reducing Residential Water Use

To reduce water usage during summer months, residents of the Durham community in Ontario, Canada, were provided with water gauges and signs to be placed over outside water faucets. The signs reminded residents to water their lawns on specific calendar days based on their house numbers and to water their lawns only when it had not rained the previous week. Critically, residents were also asked to sign commitments—which made the goals that people had set for themselves concrete and public—that they would water their lawns only on designated days and limit their watering to 1 inch per week (72 percent of residents made these commitments). Watering in the community decreased by 54 percent during the campaign relative to rates prior to the campaign.[140]

TIPS Make Behavior Change Easy

When communicators' aim is to shift individual-level behavior—whether the focus is on household energy use or civic engagement—numerous strategies can be used to make behavior change more likely. Consider the following questions as you develop your strategy to encourage behavior change:

- What positive social norms can you highlight to encourage climate-friendly behavior?
- What opportunities exist to highlight the "green Joneses" to encourage other people to engage in climate-friendly behavior?
- How can you publicly recognize individuals and groups for their climate-friendly choices?
- How can you minimize the number of choices offered to your audience to increase the likelihood that they will act?
- Are there obvious default settings that can be changed to promote climate-friendly decisions?
- What opportunities can you create for audience members to set specific targets or goals for their behavior?

CONNECTING ON CLIMATE

Quick Reference

THE BASICS: PUTTING PEOPLE FIRST

1 Put Yourself in Your Audience's Shoes

- One of the most important things climate communicators need to understand is that climate communication is not a one-size-fits-all practice.
- People's differing ***values*** (such as freedom, prosperity, or equality), ***identities*** (such as being a mother, a Democrat, or a businessperson), ***worldviews*** (such as thinking the world should be egalitarian or hierarchical), and ***personal priorities*** (such as health and finance) all shape how they respond and react to messages about climate change.
- For example, someone who values prosperity might be receptive to a message about climate change that emphasizes how clean energy solutions can unlock new economic opportunities for American families. This same person, however, would likely be frustrated by a message that emphasizes the need for sacrifice.
- ***Tip:*** *Identify the values, identities, worldviews, and personal priorities of your audience and craft communication strategies accordingly.*
- ***Tip:*** *Think about whom your audience trusts and respects and whether these people can serve as messengers.*

2 Channel the Power of Groups

- One of the most effective ways to build long-term engagement around climate change is to harness the power of social groups and networks, large and small.
- Humans are highly social creatures. They look to their groups and networks—such as church groups, company departments, parent–teacher associations, and sports clubs—for informal social norms, customs, or standards.
- When people are physically part of a group or are reminded of their membership in one, they are more likely to promote outcomes that are good for the group.
- ***Tip:*** *Weave climate change into the activities of social groups and networks, such as neighborhood associations, religious groups, clubs, or company divisions.*
- ***Tip:*** *Provide existing group leaders with climate change communication and engagement resources to activate the group's entire membership.*

CRAFTING YOUR MESSAGE: SOLUTIONS, IMPACTS, FRAMING, AND IMAGERY

3 Emphasize Solutions and Benefits

- Research indicates that it can be more effective to start with solutions rather than first giving an overview of climate change itself. This is especially true when people hear about solutions that align with their values and worldviews.
- Solutions can help reorient people toward action and opportunity and can quell feelings of hopelessness and dread.
- People's sense of personal and collective ***efficacy***—the capacity and willingness to successfully confront a challenge—is part of what drives how they respond to climate change.
- ***Tip:*** *Talk about the roles that individuals, governments (local, regional, and national), businesses, and nonprofits can all play in addressing climate change.*
- ***Tip:*** *Describe solutions that match the decision-making authority and capacity of the audience and show people the role they can play as individuals (for example, talk*

about local impacts and local solutions, not national policy and local impacts).

- ***Tip:*** *Highlight the personal and societal benefits that climate solutions will bring, such as improving health, jump-starting new economic opportunities, catalyzing technological innovation, and strengthening communities.*

Bring Climate Impacts Close to Home

- People have a hard time thinking about or acting on events that are ***psychologically distant***—events that are perceived as far in the future, physically distant, or happening to other people.
- The concept of the ***finite pool of worry*** explains that people are able to worry about only a certain number of things at a given point.
- People are much more likely to think of climate change as a relevant and urgent issue when they understand how climate change is personally affecting the lives of those immediately around them.
- ***Emotional numbing*** occurs when audiences stop responding emotionally to a message. This can happen with climate change if people are repeatedly exposed to emotionally draining messages and images.
- ***Tip:*** *Use messages that help people identify the locally relevant, personally experienced consequences and impacts that climate change is already causing.*
- ***Tip:*** *To avoid emotional numbing when communicating about the personally relevant impacts of climate change, take care to also mention solutions and actions that people can take and to focus on what impacts will occur, rather than on the exact timeline of when they will occur.*
- ***Tip:*** *Be aware of losses that may have come about as a result of recent climate impacts and focus on preparedness for the next event, rather than on the timing of the next event.*

5 Connect Climate to Issues That Matter to Your Audience

- Climate change is unique in that it affects almost everything, from our health to national security, the economy, transportation, and agriculture. Likewise, climate solutions offer the opportunity to transform almost every element of society.
- Communicators can help audiences make the connection between climate change and issues that climate change and climate solutions will affect through the use of message frames.
- ***Content frames*** describe the "who," "what," "why," and "how" of a climate change narrative and can be useful in connecting climate change to issues that matter to your audience. One common content frame is the public health implications of climate change.
- ***Structure frames*** emphasize "when," "where," and "how many" and can shape how an audience relates to a message. Popular structure frames include loss versus gain, present versus future, and local versus global.
- ***Tip:*** *Choose content frames that connect to the audience's concerns and worries.*
- ***Tip:*** *Choose structure frames that make the issue relevant and meaningful to the audience.*

6 Use Images and Stories to Make Climate Change Real

- Images and stories that inspire and empower audiences and that match the narrative and tone of accompanying text can improve people's understanding of climate change and bolster their willingness to engage.
- Technical images such as charts and graphs are appropriate only when designed and chosen with the audience's knowledge and skills in mind.

- Stories are among the best ways to connect with core human values and social identities and to build bonds between individuals and groups. They enhance people's capacity for empathy and shift frames of reference for emotional and cognitive processes.
- ***Tip:*** *Images that depict people, groups, faces, or common household items are more effective and more powerful than landscapes and nature scenes.*
- ***Tip:*** *Storytelling can help make climate change more vivid and can help people imagine the future and solutions to climate change.*

OVERCOMING BARRIERS: SCIENCE, SKEPTICISM, AND UNCERTAINTY

Make Climate Science Meaningful

- Most people have some understanding of climate change; they have a ***mental model*** of how the phenomenon works. A person's mental model of climate change can include ideas about causes, impacts, and what can be done about it.
- By understanding people's mental models, communicators can help people update their assumptions and correct misinformation.
- The ***confirmation bias*** makes people seek out information that matches their mental models, confirming what they already believe to be true.
- Most people are unfamiliar with the metrics and scales that scientists use to describe climate science. These measures are unintuitive to most people.
- ***Tip:*** *Making audience members aware of the existence of confirmation bias and encouraging them to have an open mind can help them overcome it.*
- ***Tip:*** *Present the same piece of information in multiple formats to help people understand unfamiliar numbers, metrics, and scales.*
- ***Tip:*** *Pick just a few key facts about climate change to share with an audience and put those facts into a context that audience members will understand, rather than overwhelming them with too many facts.*

8 Acknowledge Uncertainty, But Show What You Know

- No matter whom you communicate with, there will always be a few people who are uncertain about the causes of or solutions for climate change.
- Some aspects of climate change, such as the timing and extent of climate impacts and policy and technological solutions that will be available, are inherently uncertain.
- People who are skeptical about climate change often use uncertainty as an argument in favor of not taking action on the issue instead of embracing the opposite and equally plausible approach, the ***precautionary principle*** ("better safe than sorry").
- ***Tip:*** *Acknowledge the fact that there is uncertainty around elements of climate science but emphasize that uncertainty doesn't mean we shouldn't act.*
- ***Tip:*** *Use short, simple statements to highlight what is known with great certainty about climate change—that it is happening and is caused by human activities.*

9 Approach Skepticism Carefully

- There are several types of climate change skepticism.
- Skepticism that's part of the scientific process is a key component of the climate change research process because it allows scientists to talk about uncertainties that still exist.

- Skepticism based on misinformation is the result of groups that have worked to instill doubt and climate change denial among high-level decision makers and the general public.
- Skepticism due to unconscious, underlying psychological processes is called motivated reasoning. People perform mental acrobatics to avoid negative feelings, sometimes because these feelings threaten their deeply held values and beliefs.
- Countering skepticism with too many facts can backfire: hearing a myth about climate repeatedly makes it easier to believe (the ***familiarity effect***); exposure to too many arguments refuting a myth (the ***overkill effect***) makes it harder to grasp a complex truth.
- ***Tip:*** *Identify the underlying source of skepticism at play within your audience and develop a response that matches the source.*
- ***Tip:*** *Lead with the core concept that you want the audience to grasp and use only a few of the clearest and most important facts.*

TAKING IT TO THE NEXT LEVEL: CREATING THE CONDITIONS FOR CHANGE

10 Make Behavior Change Easy

- The short- and long-term goals that people set for themselves shape the information they seek out and the behavior they engage in. When people set specific goals for action and make these goals public, they are more likely to follow through *and* take action.
- When given a choice, people have a tendency to stick with the option or behavior that is preselected for them or selected automatically—the so-called ***default effect***. Defaults are omnipresent in everyday life, which means there are many opportunities to promote positive behavior change by optimizing choice settings for social and environmental benefits.
- People often adjust or change their behavior to match the behavior customary of a certain group, because humans like to comply with the ***social norms*** that govern groups they affiliate with.
- Psychologically, social rewards and receiving public feedback can spur social (and pro-environmental) behavior through the activation of social norms.
- ***Tip:*** *Presenting climate-friendly behavior as the default choice can encourage behaviors that are beneficial for the individual and the environment.*
- ***Tip:*** *Showcase positive actions that other people are taking to address climate change, especially when these people constitute a majority in a certain area or community.*
- ***Tip:*** *Highlighting climate-friendly social norms can help motivate people to undertake their own climate-friendly behavior.*

FURTHER READINGS

This list is a brief selection of relevant further reading. For a more comprehensive and up-to-date list, please visit **connectingonclimate.org**.

Focus Group and Survey Resources

Conducting Focus Groups

The Wallace Foundation compiled this workbook to provide an overview of focus groups and information about how to conduct focus group research using internal resources. *www.wallacefoundation.org/knowledge-center/after-school/collecting-and-using-data/Documents/Workbook-D-Focus-Groups.pdf*

Toolkit for Conducting Focus Groups

The Work Group for Community Health and Development at the University of Kansas developed this resource to explain the fundamentals of surveys. Specifically, the resource describes how to prepare a survey, when surveys should be conducted, how to distribute them, and how to analyze and compile results. *www.ctb.ku.edu/en/table-of-contents/assessment/assessing-community-needs-and-resources/conduct-focus-groups/main*

Survey Fundamentals: A Guide to Designing and Implementing Surveys

This guide, produced by the University of Wisconsin, describes the underlying principles of good survey design and implementation in nontechnical terms. Simple explanations lead the reader through methodology and logistics decisions, writing effective questions, and drawing conclusions from data. *www.oqi.wisc.edu/resourcelibrary/uploads/resources/Survey_Guide.pdf*

Storytelling Resources

Seeing Is Believing: A Guide to Visual Storytelling Best Practices

This best practices guide from Resource Media provides research and tools on how to incorporate visual storytelling into communication to inspire and prompt individuals to take action or change behaviors. This guide explains why images matter more than ever and how practitioners can start incorporating this reality into an effective communication strategy. *www.resource-media.org/visual-story-lab/report/*

The Story Group Climate Change Videos

The Story Group is an independent, multimedia journalism company. The organization has developed a climate change video series based on the 2014 National Climate Assessment, which explains the science behind the issue and shows how climate change is affecting real people. *www.thestorygroup.org/category/nationalclimateassessment/*

"How to Tell a Great Story"

This blog post from the Harvard Business Review provides six do's and don'ts of effective storytelling and presents two case studies to help drive these principles home. *www.blogs.hbr.org/2014/07/how-to-tell-a-great-story/*

Additional Communication Resources

The Psychology of Climate Change Communication: A Guide for Scientists, Journalists, Educators, Political Aides, and the Interested Public

This 2009 guide, published by CRED, is a companion document to this guide. It synthesizes research from across the social sciences to explain the disparity between knowledge and action on climate change. It also includes tips for presentations, lists of effective words, highlights of successful strategies, and suggestions for better communication tools. *www.guide.cred.columbia.edu/*

Communicating on Climate: 13 Steps and Guiding Principles

This guide, produced by ecoAmerica in 2013, combines the latest research on climate communication with road-tested communication best practices in an easy-to-use, practically applicable guide. *www.ecoamerica.org/research/#comm13steps*

American Climate Values 2014: Psychographic and Demographic Insights

This report summarizes top-line findings from ecoAmerica's latest round of psychographic research, which uses a sophisticated methodology to glean insights on how to effectively engage mainstream Americans on climate solutions. *www.ecoamerica.org/research/#ACV14*

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Conversation Contents

Talking Points for Repenshak

"Mow, Jeff" <jeff_mow@nps.gov>

From: "Mow, Jeff" <jeff_mow@nps.gov>
Sent: Mon Jun 10 2019 17:05:03 GMT-0600 (MDT)
To: "Alley, Lauren" <lauren_alley@nps.gov>
Subject: Talking Points for Repenshak

Laurren

I'm not sure how far you've gotten on talking points, I asked today or pressed, here are my initial thoughts:

1) We're updating exhibit panels from 10 years ago, at the time they were reflecting some of modelling work that USGS had been working.
2) At least six years ago (or as long as I have been at the park) USGS has been saying that by 2030 we'll see some of the glaciers shrinking in size to below the 25 acre threshold that is currently used to define a glacier.
3) The need to replace these panels to reflect more recent understanding on the impacts of glacial melt was in 2017.
4) Responding to the impacts of wildfire has been the dominant issue in much of our climate change impact messaging with 3 out of the last 4 years having large fires in the park.
5) The park has hundreds of waysides and exhibit panels that are recorded, updated, and replaced through deferred maintenance funding. The park is constantly adjusting priorities for deferred maintenance needs. There are numerous other panels regarding numerous other topics that are in need of replacement and updating.

Jeff Mow
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"Alley, Lauren" <lauren_alley@nps.gov>

From: "Alley, Lauren" <lauren_alley@nps.gov>

Sent: Mon Jun 10 2019 20:19:59 GMT-0600 (MDT)
To: "Mow, Jeff" <jeff_mow@nps.gov>
Subject: Re: Talking Points for Repenshak

I think we should use the desk statement we/USGS developed for DOI for this one and also link to the 2015 glacier margins study.

Let me know if you'd like to respond, or me. I'm happy to.

> Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.
>
> The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.
>
> USGS regularly publicizes their research efforts. The National Park Service does not typically issue press releases for new interpretive displays or park signage.
>
> The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

On Mon, Jun 10, 2019 at 5:05 PM Mow, Jeff <jeff_mow@nps.gov> wrote:

> Laurren
>
> I'm not sure how far you've gotten on talking points, I asked today or pressed, here are my initial thoughts:
>
> 1) We're updating exhibit panels from 10 years ago, at the time they were reflecting some of modelling work that USGS had been working.
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> 3) The need to replace these panels to reflect more recent understanding on the impacts of glacial melt was in 2017.
> 4) Responding to the impacts of wildfire has been the dominant issue in much of our climate change impact messaging with 3 out of the last 4 years having large fires in the park.
> 5) The park has hundreds of waysides and exhibit panels that are recorded, updated, and replaced through deferred maintenance funding. The park is constantly adjusting priorities for deferred maintenance needs. There are numerous other panels regarding numerous other topics that are in need of replacement and updating.
>
> **Jeff Mow**
> **Superintendent**
> **Glacier National Park**
> **P.O. Box 128**

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Jeff Mow <jeff_mow@nps.gov>

From:	Jeff Mow <jeff_mow@nps.gov>
Sent:	Mon Jun 10 2019 20:29:05 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
Subject:	Re: Talking Points for Repenshak

If you think we're ready, I'll use what you provided. Though I would still like to make the case that both wildfires and visitor use management have dominated our public messaging, budget prioritization, and our efforts to respond the impacts of climate change.

Sent from my iPad

On Jun 10, 2019, at 8:19 PM, Alley, Lauren <lauren_alley@nps.gov> wrote:

> I think we should use the desk statement we/USGS developed for DOI for this one and also link to the 2015 glacier margins study.
>
> Let me know if you'd like to respond, or me. I'm happy to.
>
>> Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.
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>
> **Lauren Alley**

Management Assistant
Glacier National Park
406.888.5838

On Mon, Jun 10, 2019 at 5:05 PM Mow, Jeff <jeff_mow@nps.gov> wrote:

Laurren

I'm not sure how far you've gotten on talking points, I asked today or pressed, here are my initial thoughts:

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"Alley, Lauren" <lauren_alley@nps.gov>

From:	"Alley, Lauren" <lauren_alley@nps.gov>
Sent:	Mon Jun 10 2019 20:48:29 GMT-0600 (MDT)
To:	Jeff Mow <jeff_mow@nps.gov>
Subject:	Re: Talking Points for Repenshak

Sounds good. The statement below was what everyone has been providing (DOI, NPS, GLAC) to be consistent.

We're also developing more extensive talking points for park staff, but those aren't ready yet.

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

On Mon, Jun 10, 2019 at 8:29 PM Jeff Mow <jeff_mow@nps.gov> wrote:

> If you think we're ready, I'll use what you provided. Though I would still like to make the case that both wildfires and visitor use management have dominated our public messaging, budget prioritization, and our efforts to respond the impacts of climate change.
>
> Sent from my iPad
>
> On Jun 10, 2019, at 8:19 PM, Alley, Lauren <lauren_alley@nps.gov> wrote:
>
>> I think we should use the desk statement we/USGS developed for DOI for this one and also link to the 2015 glacier margins study.
>>
>> Let me know if you'd like to respond, or me. I'm happy to.
>>
>>> Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.
>>>
>>> The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.
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>>
>> **Lauren Alley**
>> Management Assistant
>> Glacier National Park
>> 406.888.5838
>
> On Mon, Jun 10, 2019 at 5:05 PM Mow, Jeff <jeff_mow@nps.gov> wrote:
>
>> Laurren
>>
>> I'm not sure how far you've gotten on talking points, I asked today or pressed, here are my initial thoughts:

1) We're updating exhibit panels from 10 years ago, at the time they were reflecting some of modelling work that USGS had been working.
2) At least six years ago (or as long as I have been at the park) USGS has been saying that by 2030 we'll see some of the glaciers shrinking in size to below the 25 acre threshold that is currently used to define a glacier.
3) The need to replace these panels to reflect more recent understanding on the impacts of glacial melt was in 2017.
4) Responding to the impacts of wildfire has been the dominant issue in much of our climate change impact messaging with 3 out of the last 4 years having large fires in the park.
5) The park has hundreds of waysides and exhibit panels that are recorded, updated, and replaced through deferred maintenance funding. The park is constantly adjusting priorities for deferred maintenance needs. There are numerous other panels regarding numerous other topics that are in need of replacement and updating.

Jeff Mow
Superintendent
Glacier National Park
P.O. Box 128
West Glacier, MT 59938
office: 406 888 7901
mobile: 406 250 1431
fax: 406 888 7904

Conversation Contents

Re: [EXTERNAL] Wash Times inquiry/Glacier National Park Signage

"Kupper, Kathy" <kathy_kupper@nps.gov>

From:	"Kupper, Kathy" <kathy_kupper@nps.gov>
Sent:	Mon Jun 10 2019 12:39:15 GMT-0600 (MDT)
To:	"Puckett, Catherine" <cpuckett@usgs.gov>, "Alley, Lauren" <lauren_alley@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>
CC:	Daniel Fagre <dan_fagre@usgs.gov>, "McClymont, Ryan" <rmcclymont@usgs.gov>, "Armstrong, Karen" <karmstrong@usgs.gov>
Subject:	Re: [EXTERNAL] Wash Times inquiry/Glacier National Park Signage

Hi All,

I did respond to the reporter with the statement. In a follow up she asked if I could confirm that the park is removing the "2020" signs. Have they already been removed or will they be?

Thank you,
Kathy

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

The National Park Service cares for special places saved by the American people so that all may experience our heritage.

EXPERIENCE YOUR AMERICA ®

On Mon, Jun 10, 2019 at 1:37 PM Puckett, Catherine <cpuckett@usgs.gov> wrote:

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> *Statement*

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🐝Catherine Puckett
Acting Western States Communications Chief
USGS Office of Communications
352-377-2469 (O) 352-278-0165 (cell)
cpuckett@usgs.gov

On Mon, Jun 10, 2019 at 11:50 AM Valerie Richardson <vrichardson@washingtontimes.com> wrote:

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>
> Thanks very much,
>
> Valerie
>
> --
> **Valerie Richardson** | National Reporter / Denver and Omaha
> cell 303-507-3856 | office 303.470.7078 | @ValRichardson17
>
> The Washington Times
> 3600 New York Ave NE | Washington DC, 20002
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"Alley, Lauren" <lauren_alley@nps.gov>

From:	"Alley, Lauren" <lauren_alley@nps.gov>
Sent:	Mon Jun 10 2019 13:57:23 GMT-0600 (MDT)
To:	"Kupper, Kathy" <kathy_kupper@nps.gov>
CC:	"Puckett, Catherine" <cpuckett@usgs.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, "McClymont, Ryan" <rmcclymont@usgs.gov>, "Armstrong, Karen" <karmstrong@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Re: [EXTERNAL] Wash Times inquiry/Glacier National Park Signage

Kathy -

The park has a number of interpretive exhibits about glaciers, some of which contain information based on early glacial recession research and modeling. Those will be updated as capacity and funding allows, similar to other outdated exhibits on other topics.

Lauren Alley
Management Assistant
Glacier National Park
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From:	"Kupper, Kathy" <kathy_kupper@nps.gov>
Sent:	Mon Jun 10 2019 13:58:55 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
CC:	"Puckett, Catherine" <cpuckett@usgs.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, "McClymont, Ryan" <rmcclymont@usgs.gov>, "Armstrong, Karen" <karmstrong@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Re: [EXTERNAL] Wash Times inquiry/Glacier National Park Signage

Thanks Lauren!

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

The National Park Service cares for special places saved by the American people so that all may experience our heritage.

EXPERIENCE YOUR AMERICA ®

On Mon, Jun 10, 2019 at 3:57 PM Alley, Lauren <lauren_alley@nps.gov> wrote:

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>
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Thanks very much,

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Conversation Contents

Exhibit text and/or photos ASAP?

Attachments:

/7. Exhibit text and/or photos ASAP?/2.1 GL-07-400rev2.pdf
/7. Exhibit text and/or photos ASAP?/2.2 GL-07-400 May 2019 Revisions.pdf
/7. Exhibit text and/or photos ASAP?/2.3 GL-06-300 updated MAY 2019.pdf
/7. Exhibit text and/or photos ASAP?/2.4 GL-06-300rev1.pdf
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Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Sat Jun 08 2019 15:05:54 GMT-0600 (MDT)
To:	lee_rademaker@nps.gov, debby_smith@nps.gov
CC:	Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject:	Exhibit text and/or photos ASAP?

Hey Lee and Debby - Are either of you working today or tomorrow? There are some media outlets reporting about our Glacier exhibit updates and I'd like to get a sense of how things looked before and after so we can put some info on the web if needed to clear up confusion. My guess is that by Monday morning, main stream media will be calling. If you have text or photos or anything, I would really appreciate it. Cc to Tracy and Bill as well. Thanks all. Sent from my iPad

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Sat Jun 08 2019 16:20:37 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, "Mensch, D" <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Here are some attachments and some background.

The exhibits in the St. Mary Visitor Center were probably installed in 2010. There had been several planning and design meetings with Harpers Ferry Center personnel in the several years

previous. Mark Wagner was the lead on the exhibit redesigns. Sheri Forbes was the Chief of Interpretation. I was actually not involved in any aspect of the project or meetings from start to finish, so my memory on the exact dates is fuzzy. My guess on the year is based on the final planning document from the fabricator of the exhibits. The planning and design most surely happened much prior to that date. Mark Wagner may know more specifics.

In any case the exhibits that deal with glacial retreat were based on the USGS information that was available at that time. Since then their research has continued and evolved to include a more refined picture of glaciers in the park. Like much of scientific research, there are often not concrete black and white answers to basic questions, and that is often hard for some people to grapple with.

In the late summer, or fall, of 2017 staff from the USGS informed us, the media staff, that there were dates in the exhibits near the relief map at St. Mary that were not consistent with current research and asked that we change them. We were unable to do that for the 2018 season. At the end of the season we removed the exhibits and made changes to the original files. Those changes went through review by NPS and USGS staff and our sign shop was able to fabricate them and have them installed just prior to the opening of the Visitor Center this spring. Attached you should find the new exhibits and the former exhibits as PDF files.

There are also exhibits at the Apgar and St. Mary Visitor Center plazas, outside, that have dates that need changing. Those exhibits date from 2007. There are two exhibits that I know of at Logan Pass that likewise have these dates and should be changed out. In 2018 two new glacier exhibits replaced the one exhibit at Jackson Glacier Overlook. The old one had the 2030 date on it as well. It also contained images from the computer projection model, that was based on USGS work published in the early 2000s, I think 2003. This oldexhibit was designed in 2006 in coordination with Leigh Welling, who was in charge of the Crown of the Continent Research Learning Center at the time. I remember the date because I worked on refining her files while I was in Seattle that entire summer. She went from Glacier to a position in Colorado for the Natural Resources Division, where she dealt specifically with climate change issues.

A more complete review of other wayside exhibits will show mentions of climate change and some may have dates, although none come to mind at the moment. I can provide copies of these other exhibits if you wish, but I don't want to overload this particular email. We have them to view when needed.

Exhibit GL-07-400 May 2019 Revisions.pdf is the exhibit at the relief map that has the button to push for locations of the glaciers. It does not mention a specific date for the complete glacial melt. GL-07-400rev2.pdf is the original file as installed when the rest of the exhibits went in.

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Daniel/Tracy feel free to provide any details or updates that I may have missed or gotten wrong.

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--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Mon Jun 10 2019 08:00:57 GMT-0600 (MDT)
To:	"Mow, Jeff" <jeff_mow@nps.gov>, Connie Stahr <connie_stahr@nps.gov>
CC:	"Alley, Lauren" <lauren_alley@nps.gov>, Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Fwd: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Jeff,

For our discussion and your information. If we need additional detail in regard to timing, I could reach out to Mark Wagner and/or HFC.

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930

---------- Forwarded message ---------
From: **Hayden, William** <bill_hayden@nps.gov>
Date: Sat, Jun 8, 2019 at 4:20 PM
Subject: Re: Exhibit text and/or photos ASAP?
~~~~~~~~~~~~~~~~~~~~~~~~~

To: Lauren Alley <lauren_alley@nps.gov>
Cc: Lee Rademaker <lee_rademaker@nps.gov>, Mensch, D <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>

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Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

GOODBYE TO THE GLACIERS

The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. They are now rapidly shrinking due to human-caused climate change. Computer models indicate the glaciers will all be gone by the year 2020.

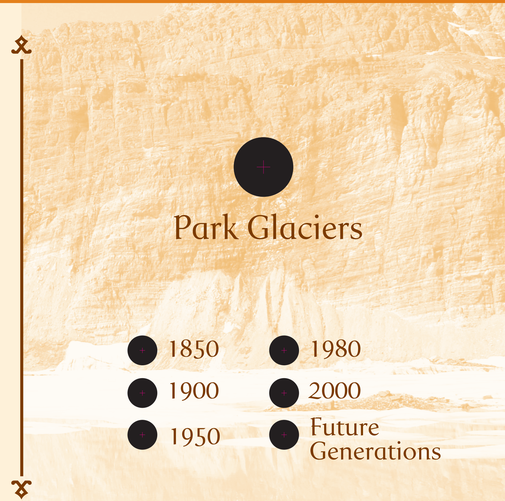
Glacier National Park was named for the sculpting actions of the Pleistocene glaciers that covered this landscape 12,000 to 130,000 years ago.

Park glaciers between 1850 and 2020

- 1850
- 1900
- 1950
- 1980
- 2000
- 2020 *(projected)*

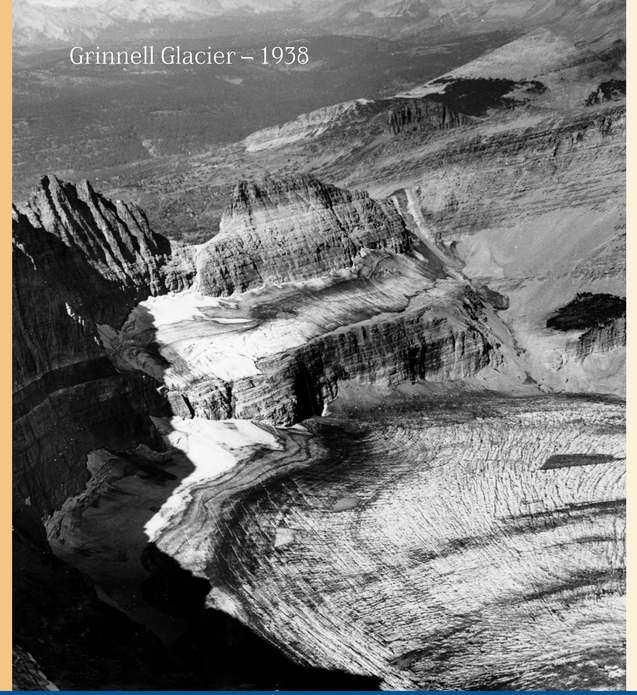
GOODBYE TO THE GLACIERS

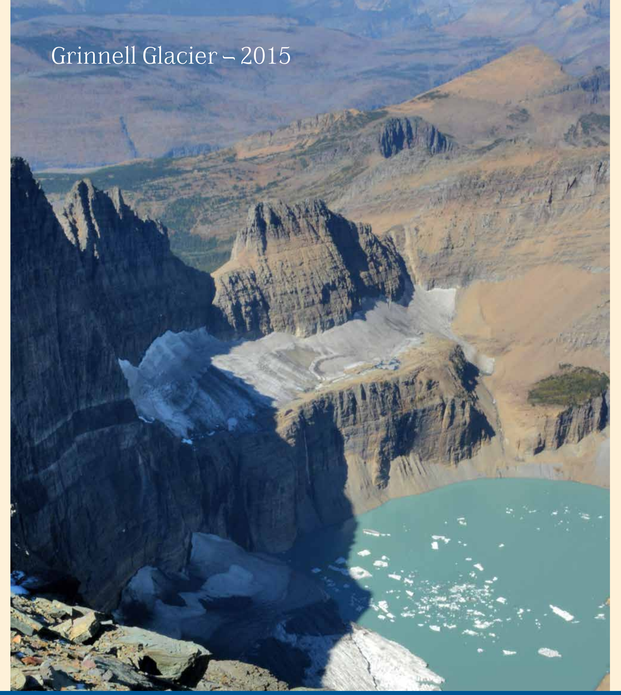
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum size and number around 1850, at the end of the Little Ice Age. Currently, they are rapidly shrinking due to human-accelerated climate change. When they will completely disappear, however, depends on how and when we act.



Glaciers are moving masses of ice. During the Pleistocene—12,000–130,000 years ago—the massive glaciers shaping this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





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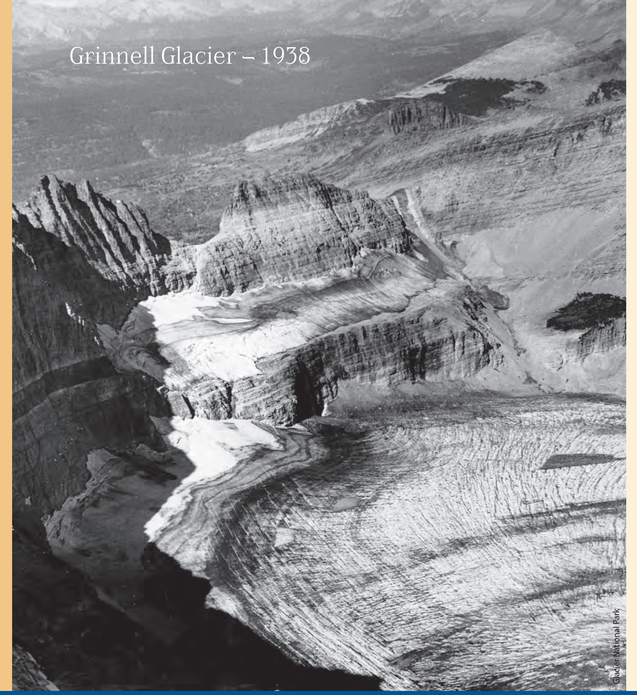

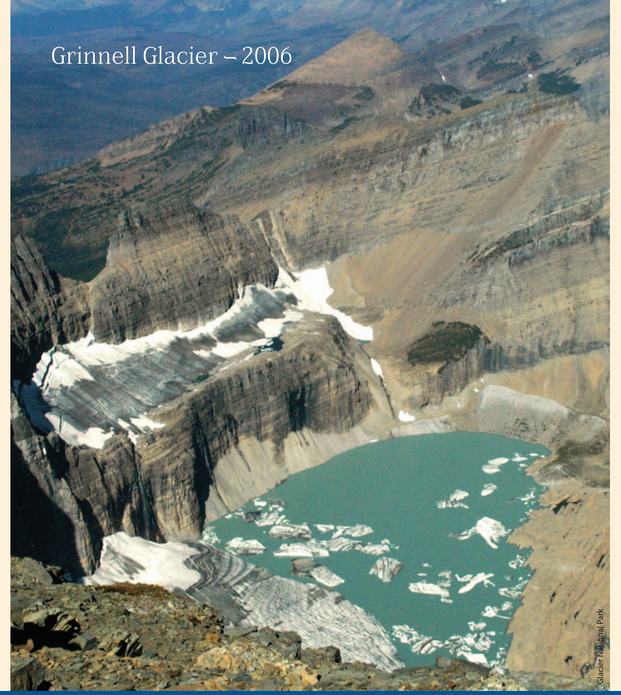

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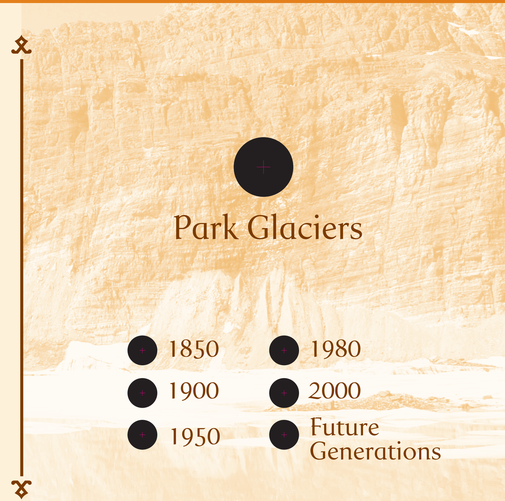

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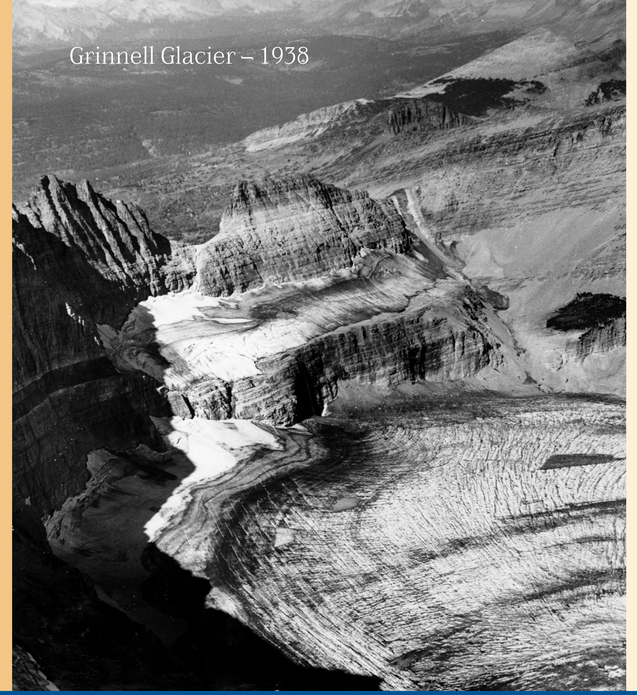

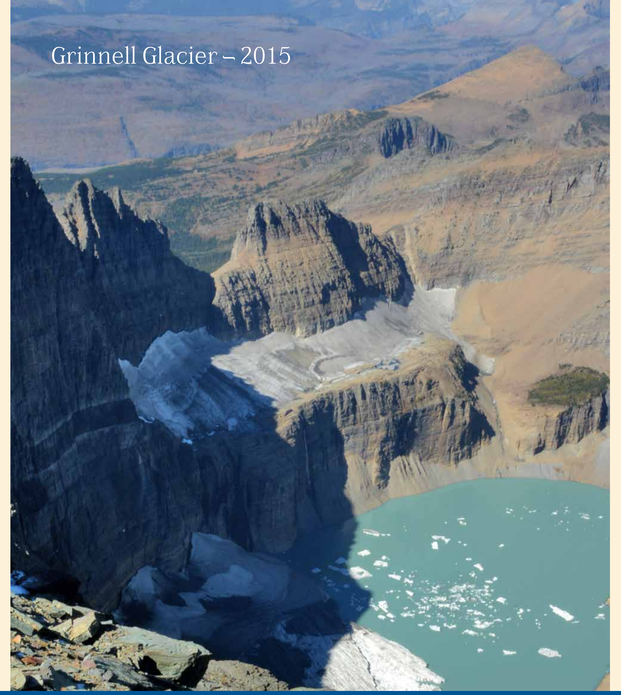

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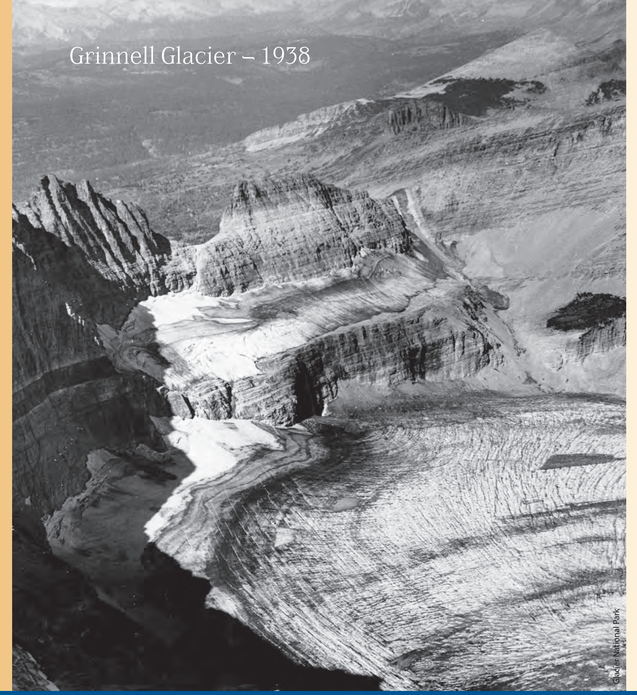

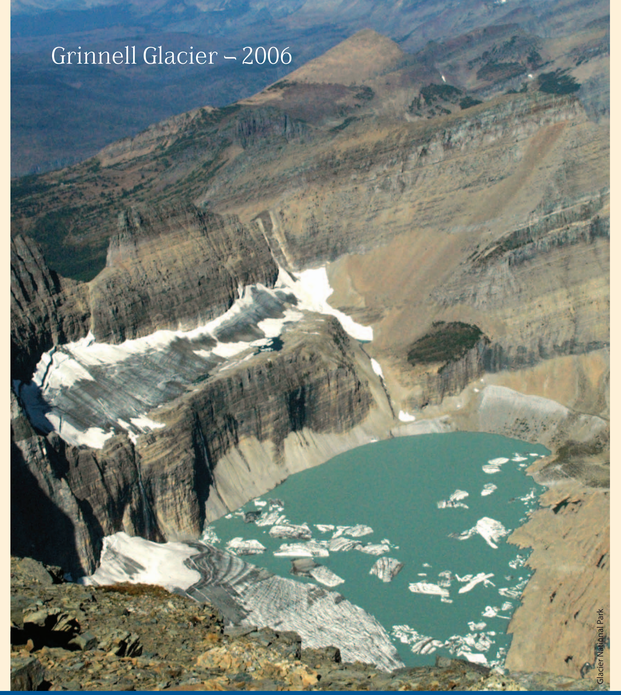

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Fwd: Exhibit text and/or photos ASAP?

Attachments:

/8. Fwd: Exhibit text and/or photos ASAP?/1.1 GL-07-400rev2.pdf
/8. Fwd: Exhibit text and/or photos ASAP?/1.2 GL-07-400 May 2019 Revisions.pdf
/8. Fwd: Exhibit text and/or photos ASAP?/1.3 GL-06-300 updated MAY 2019.pdf
/8. Fwd: Exhibit text and/or photos ASAP?/1.4 GL-06-300rev1.pdf

Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Sun Jun 09 2019 18:48:18 GMT-0600 (MDT)
To:	jeff_mow@nps.gov
Subject:	Fwd: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Sent from my iPhone

Begin forwarded message:

From: "Hayden, William" <bill_hayden@nps.gov>
To: Lauren Alley <lauren_alley@nps.gov>
Cc: Lee Rademaker <lee_rademaker@nps.gov>, "Mensch, D" <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject: Re: Exhibit text and/or photos ASAP?

Here are some attachments and some background.

The exhibits in the St. Mary Visitor Center were probably installed in 2010. There had been several planning and design meetings with Harpers Ferry Center personnel in the several years previous. Mark Wagner was the lead on the exhibit redesigns. Sheri Forbes was the Chief of Interpretation. I was actually not involved in any aspect of the project or meetings from start to finish, so my memory on the exact dates is fuzzy. My guess on the year is based on the final planning document from the fabricator of the exhibits. The planning and design most surely happened much prior to that date. Mark Wagner may know more specifics.

In any case the exhibits that deal with glacial retreat were based on the USGS information that was available at that time. Since then their research has continued and evolved to include a more refined picture of glaciers in the park. Like much of scientific research, there are often not concrete black and white answers to basic

questions, and that is often hard for some people to grapple with.

In the late summer, or fall, of 2017 staff from the USGS informed us, the media staff, that there were dates in the exhibits near the relief map at St. Mary that were not consistent with current research and asked that we change them. We were unable to do that for the 2018 season. At the end of the season we removed the exhibits and made changes to the original files. Those changes went through review by NPS and USGS staff and our sign shop was able to fabricate them and have them installed just prior to the opening of the Visitor Center this spring. Attached you should find the new exhibits and the former exhibits as PDF files.

There are also exhibits at the Apgar and St. Mary Visitor Center plazas, outside, that have dates that need changing. Those exhibits date from 2007. There are two exhibits that I know of at Logan Pass that likewise have these dates and should be changed out. In 2018 two new glacier exhibits replaced the one exhibit at Jackson Glacier Overlook. The old one had the 2030 date on it as well. It also contained images from the computer projection model, that was based on USGS work published in the early 2000s, I think 2003. This oldexhibit was designed in 2006 in coordination with Leigh Welling, who was in charge of the Crown of the Continent Research Learning Center at the time. I remember the date because I worked on refining her files while I was in Seattle that entire summer. She went from Glacier to a position in Colorado for the Natural Resources Division, where she dealt specifically with climate change issues.

A more complete review of other wayside exhibits will show mentions of climate change and some may have dates, although none come to mind at the moment. I can provide copies of these other exhibits if you wish, but I don't want to overload this particular email. We have them to view when needed.

Exhibit GL-07-400 May 2019 Revisions.pdf is the exhibit at the relief map that has the button to push for locations of the glaciers. It does not mention a specific date for the complete glacial melt. GL-07-400rev2.pdf is the original file as installed when the rest of the exhibits went in.

Exhibit GL-06-300rev1.pdf is the as installed original exhibit that is in front of one of the windows looking out at the mountains. It mentions also that 202 is the year the glaciers will be melted. GL-06-300 updated MAY 2019.pdf is the new file that was installed last month.

Daniel/Tracy feel free to provide any details or updates that I may have missed or gotten wrong.

On Sat, Jun 8, 2019 at 3:05 PM Lauren Alley <lauren_alley@nps.gov> wrote:

> Hey Lee and Debby -
>
> Are either of you working today or tomorrow?
>
> There are some media outlets reporting about our Glacier exhibit updates and I'd like to get a sense of how things looked before and after so we can put some info on the web if needed to clear up confusion.
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> Cc to Tracy and Bill as well.
>
> Thanks all.
>
> Sent from my iPad

--

Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

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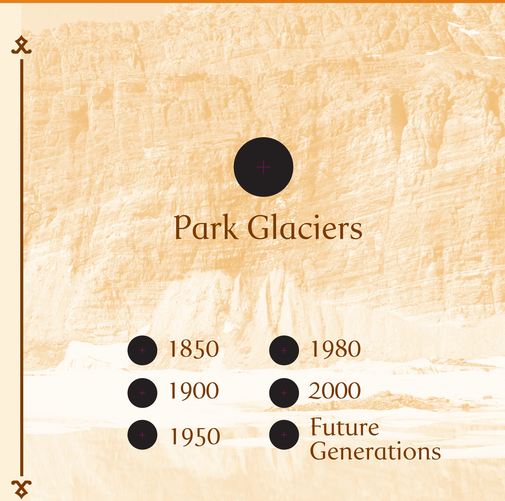

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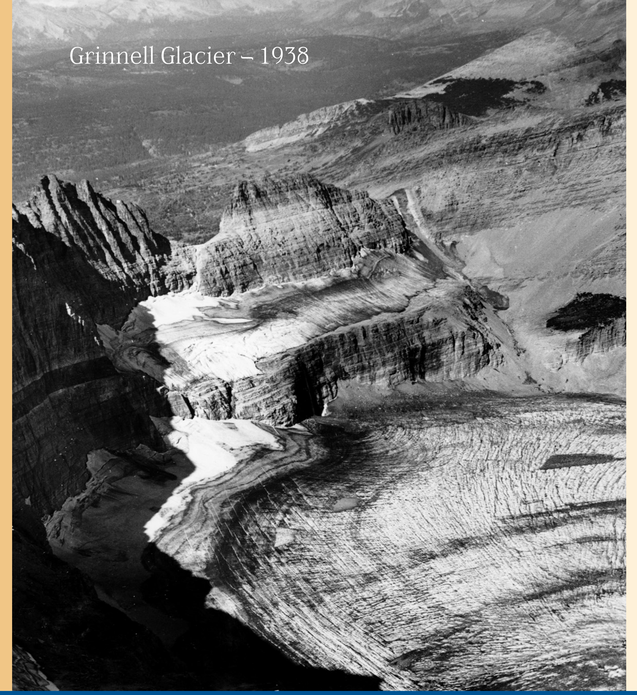

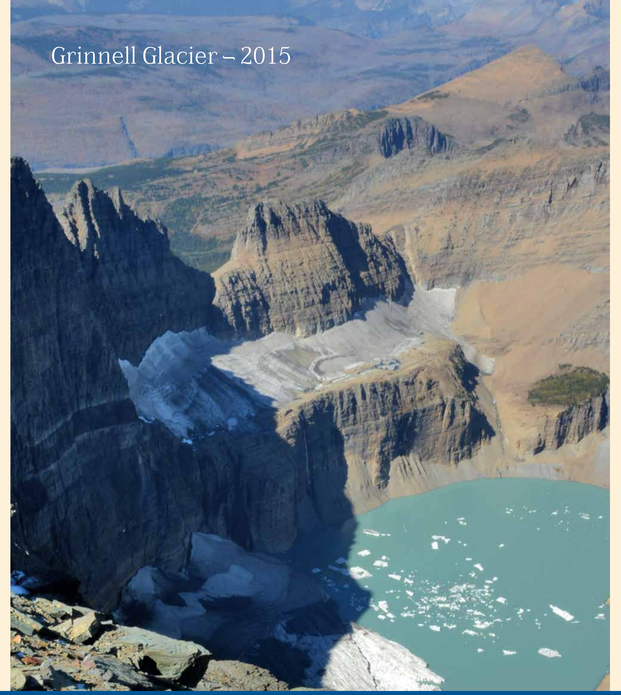

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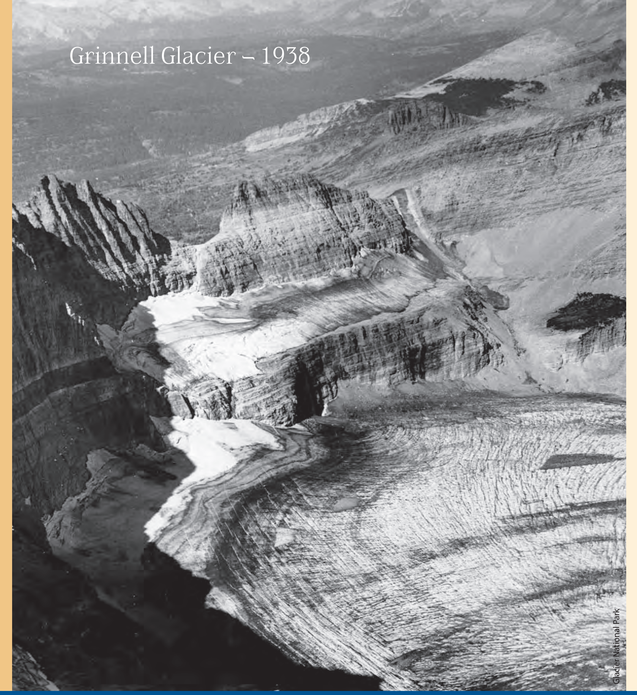

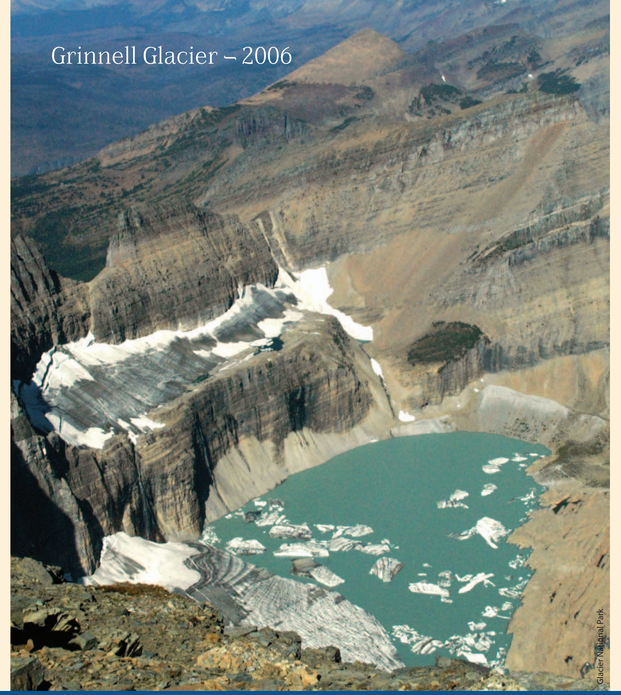

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GLACIERS ON THE MOVE

Conversation Contents

Re: Exhibit text and/or photos ASAP?

Deborah Smith <debby_smith@nps.gov>

From:	Deborah Smith <debby_smith@nps.gov>
Sent:	Sat Jun 08 2019 16:03:03 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>, lee_rademaker@nps.gov
CC:	Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject:	Re: Exhibit text and/or photos ASAP?

Actually Bill (or Daniel for sure) should have all of this. I'm in town right now, but I can look when I get back and I think I also have the new panel in my email from when Daniel sent it to Lee and I to proof. I'm around this weekend, but Lee is back in Helena this weekend.

I'll be in touch...

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

-------- Original Message --------
From: Lauren Alley <lauren_alley@nps.gov>
Date: Sat, June 08, 2019 3:05 PM -0600
To: lee_rademaker@nps.gov, debby_smith@nps.gov
CC: Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject: Exhibit text and/or photos ASAP?

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Are either of you working today or tomorrow?

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My guess is that by Monday morning, main stream media will be calling.

If you have text or photos or anything, I would really appreciate it.

Cc to Tracy and Bill as well.

Thanks all.

Sent from my iPad

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Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Attachments:

/10. Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage/1.1 image001.png
/10. Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage/1.2 image002.png

Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Sat Jun 08 2019 15:12:11 GMT-0600 (MDT)
To:	dan_fagre@usgs.gov, Melissa_Sladek@nps.gov, tara_carolin@nps.gov, jeff_mow@nps.gov, tracy_ammerman@nps.gov, phil_wilson@nps.gov
Subject:	Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage
Attachments:	image001.png image002.png

All -

I am circling back with you on what WASO and DOI have proposed below. From media outlets, it appears they're already using it (the stuff in gray text that the park didn't develop). The story has gone fairly viral in the last 24 hours.

Dan - do you want us to use this, or something else?

From park perspective I'm hoping to track down exhibit text so we can hopefully proactively address this.

My main objective is to identify exactly what NPS/USGS said about 2020 and publicly acknowledge that via website to clear up any confusion and for transparency. Certainly nobody wants to "quietly" do something or hide something. If anyone has any proposed text for this specific point, I'd welcome it.

Thanks to anyone who can provide input over the weekend. My guess is that by Monday at 8 am, we're going to get even more calls.

Sent from my iPad

Begin forwarded message:

> **From:** "Kupper, Kathy" <kathy_kupper@nps.gov>
> **Date:** June 7, 2019 at 3:24:56 PM MDT
> **To:** "Block, Molly" <molly_block@ios.doi.gov>
> **Cc:** April Slayton <april_slayton@nps.gov>, "Barnum, Jeremy" <jeremy_barnum@nps.gov>, Karen Armstrong <karmstrong@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon

<marco_deleon@nps.gov>, Paul Laustsen <plaustsen@usgs.gov>, Ryan McClymont <rmcclymont@usgs.gov>, Catherine Puckett <cpuckett@usgs.gov>
Subject: Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Hi Molly,

April and I are OK with the statement. We are looping in park staff and a couple of other SMEs for awareness and their input on the statement. Dan Fagre from USGS (dan_fagre@usgs.gov) is the SME that can also take calls if needed.

Thank you,
Kathy

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

The National Park Service cares for special places saved by the American people so that all may experience our heritage.

EXPERIENCE YOUR AMERICA ®

On Fri, Jun 7, 2019 at 5:00 PM Block, Molly <molly_block@ios.doi.gov> wrote:
Adding the Park Service. Let's get a desk statement we can send around. Here's what I shared with the Daily Caller:

Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.

The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.

USGS regularly publicizes their research efforts. The National Park Service does not typically issue press releases for new interpretive displays or park signage.

The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.

On Fri, Jun 7, 2019 at 4:53 PM Karen Armstrong <karmstrong@usgs.gov> wrote:
How would you like to handle?

Sent from my iPhone

Begin forwarded message:

From: Cheyenne MacDonald
<Cheyenne.Macdonald@mailonline.com>
Date: June 7, 2019 at 4:48:07 PM EDT
To: "karmstrong@usgs.gov" <karmstrong@usgs.gov>
Subject: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Hi Karen! My name is Cheyenne, I'm the Science & Tech Editor at Dailymail.com. I'm reaching out in regards to a report that's been going around today, was hoping to get some additional context and verify the claims being made.

The report, linked here, https://dailycaller.com/2019/06/07/national-park-glacier-warnings/ , claims signs at Glacier National Park that warned glaciers will disappear by 2020 due to climate change have been 'quietly removed' after 'several winters of heavy snowfall threw off climate model projections.'

I would appreciate if you could clarify a few points:

-Have the signs really been changed? If so, when and why

-What do the latest models suggest about the state of glaciers in the park?

-Is there any weight to claims that glaciers have grown in recent years due to heavier snowfall?

Any additional information you can provide on the subject would be great.

Thanks so much.

Best,

Cheyenne

Cheyenne MacDonald

US Science & Technology Editor

Daily Mail Online | @_cheymac

51 Astor Place, 9th Floor, New York, NY 10003

cid:C0FFDDA4-A7B5-4A83-82B0-6D14B1369EE4

cid:1B9B73EA-D6E8-4333-8EAD-98E24A75B563

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--
Molly Block
Press Secretary
U.S. Department of the Interior

Jeff Mow <jeff_mow@nps.gov>

From:	Jeff Mow <jeff_mow@nps.gov>
Sent:	Sat Jun 08 2019 15:54:56 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	dan_fagre@usgs.gov, Melissa_Sladek@nps.gov, tara_carolin@nps.gov, tracy_ammerman@nps.gov, phil_wilson@nps.gov
Subject:	Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage

All

Debby and I touched base on this yesterday and we said we'd circle up on the process on Monday. A couple of things I'd like to know

1) how old are these exhibits
2) when did we put these into pmis for replacement funding
3) how many exhibits overall do we have in pmis for cyclic funding replacement
4) am I correct in assuming that the lion's share of exhibit panels that make reference to When the glaciers will disappear use the 2030 date. The 2020 date is an outlier.

To me there is a backstory that may have a connection to DM. We have so many trails, roads, restrooms, campgrounds, water systems, and wayside exhibits that are in line for replacement or rehabilitation and as we all know it can takes years for things to move up in the priority list.

I have no idea if these exhibits are in The system like the interpretive waysides are so this theme may not apply.

Sent from my iPhone

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On Fri, Jun 7, 2019 at 5:00 PM Block, Molly <molly_block@ios.doi.gov> wrote:

Adding the Park Service. Let's get a desk statement we can send around. Here's what I shared with the Daily Caller:

Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.

The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.

USGS regularly publicizes their research efforts. The National Park Service does not typically issue press releases for new interpretive displays or park signage.

The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.

On Fri, Jun 7, 2019 at 4:53 PM Karen Armstrong <karmstrong@usgs.gov> wrote:

How would you like to handle?

Sent from my iPhone

Begin forwarded message:

From: Cheyenne MacDonald <Cheyenne.Macdonald@mailonline.com>
Date: June 7, 2019 at 4:48:07 PM EDT
To: "karmstrong@usgs.gov" <karmstrong@usgs.gov>
Subject: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Hi Karen! My name is Cheyenne, I'm the Science & Tech Editor at Dailymail.com. I'm reaching out in regards to a report that's been going around today, was hoping to get some additional context and verify the claims being made.

The report, linked here, https://dailycaller.com/2019/06/07/national-park-glacier-warnings/ , claims signs at Glacier National Park that warned glaciers will disappear by 2020 due to climate change have been 'quietly removed' after 'several winters of heavy snowfall threw off climate model projections.'

I would appreciate if you could clarify a few points:

-Have the signs really been changed? If so, when and why

-What do the latest models suggest about the state of glaciers in the park?

-Is there any weight to claims that glaciers have grown in recent years due to heavier snowfall?

Any additional information you can provide on the subject would be great.

Thanks so much.

Best,

Cheyenne

Cheyenne MacDonald

US Science & Technology Editor

Daily Mail Online | @_cheymac

51 Astor Place, 9th Floor, New York, NY 10003

<image001.png>

<image002.png>

Disclaimer

This e-mail and any attached files are intended for the named addressee only. It contains information, which may be confidential and legally

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--
Molly Block
Press Secretary
U.S. Department of the Interior

Conversation Contents

Fwd: Media Inquiry: [EXTERNAL] Is this true?

Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Fri Jun 07 2019 13:57:16 GMT-0600 (MDT)
To:	teagan_tomlin@nps.gov
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

Sent from my iPhone

Begin forwarded message:

From: "Kupper, Kathy" <kathy_kupper@nps.gov>
Date: June 7, 2019 at 6:26:53 AM MDT
To: "Alley, Lauren" <lauren_alley@nps.gov>
Cc: Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov>
Subject: Re: Media Inquiry: [EXTERNAL] Is this true?

Thanks Lauren!

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

The National Park Service cares for special places saved by the American people so that all may experience our heritage.

EXPERIENCE YOUR AMERICA ®

On Thu, Jun 6, 2019 at 8:08 PM Alley, Lauren <lauren_alley@nps.gov> wrote:

Kathy/all,

Please see below for some context. I'm copying USGS public affairs for the Northern Rockies (Sarah Beldin) and the lead USGS scientist (Dan Fagre) on this response in case you or DOI have any follow up questions for us.

Cheers,

Lauren

The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.

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A paper published in 2003 predicted that the glaciers in Glacier National Park would be gone by 2030, based on modeling that the glaciers would continue to melt at the same rate that they had over the previous decades.

Further research in the late 2000s revealed specific glaciers were melting even faster than the rate used in the 2003 model, which began predictions that at least some of the glaciers may be gone as early as 2020. (See page 80 of the linked article.)

Research on the glaciers has continued. In the last several years, USGS has released peer reviewed research on glacial retreat that provide greater accuracy than was available early on in the research project, including improved satellite images and a greater understanding of how site specific conditions affect glacier size and melt rate. The research shows variability in the rate at which individual glaciers are melting though the overall declining trend continues. Recent data show reductions in size range from 9%-96%, averaging a 68% reduction in glacial area overall.

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In the past three years, the park has used the following statement when responding to the multiple media requests it receives about glacial retreat:

"There are currently 26 glaciers in the park. Scientific models project that many will no longer meet the size criteria used to define a glacier sometime between 2030 and 2080."

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

On Thu, Jun 6, 2019 at 12:11 PM Kupper, Kathy <kathy_kupper@nps.gov> wrote:

Hi Lauren,

DOI received a media inquiry regarding the following article. Can you please let us know if the info in it is correct and/or any related background?
https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2i

hllc

Thank you,
Kathy

Kathy Kupper
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Office of Communications
National Park Service
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www.nps.gov

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"Lacayo, Vanessa" <vanessa_lacayo@nps.gov>

From:	"Lacayo, Vanessa" <vanessa_lacayo@nps.gov>
Sent:	Fri Jun 07 2019 14:23:32 GMT-0600 (MDT)
To:	"Kupper, Kathy" <kathy_kupper@nps.gov>
CC:	"Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov>, Paul Laustsen <plaustsen@usgs.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Just a quick update, I spoke to Lauren and understand the park is receiving several calls on this issue. Sounds like Rush Limbaugh referenced this in his show, I cannot find the clip though. Either way, I touched base with Paul Laustsen and Dan Fagre with USGS on this issue and they will be fielding media calls.

Paul, please let us know if/how we can be supportive on the NPS end.

Thanks!

Take Care,
Vanessa Lacayo
Public Affairs Specialist
National Park Service
Intermountain Regional Office
Office of Communications and Legislation
Office: (303) 969-2062
vanessa_lacayo@nps.gov

On Fri, Jun 7, 2019 at 6:27 AM Kupper, Kathy <kathy_kupper@nps.gov> wrote:
Thanks Lauren!

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Public Affairs Specialist
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National Park Service
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Thank you,
Kathy

Kathy Kupper
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"Kupper, Kathy" <kathy_kupper@nps.gov>

From:	"Kupper, Kathy" <kathy_kupper@nps.gov>
Sent:	Fri Jun 07 2019 14:34:39 GMT-0600 (MDT)
To:	"Lacayo, Vanessa" <vanessa_lacayo@nps.gov>
	"Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum

CC: <jeremy_barnum@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov>, Paul Laustsen <plaustsen@usgs.gov>

Subject: Re: Media Inquiry: [EXTERNAL] Is this true?

Thanks for letting us know.

Kathy

Kathy Kupper
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Office of Communications
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On Fri, Jun 7, 2019 at 4:24 PM Lacayo, Vanessa <vanessa_lacayo@nps.gov> wrote:

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Take Care,
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Public Affairs Specialist
National Park Service
Intermountain Regional Office
Office of Communications and Legislation
Office: (303) 969-2062
vanessa_lacayo@nps.gov

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Kathy Kupper
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"Laustsen, Paul" <plaustsen@usgs.gov>

From:	"Laustsen, Paul" <plaustsen@usgs.gov>
Sent:	Fri Jun 07 2019 14:38:47 GMT-0600 (MDT)
To:	"Lacayo, Vanessa" <vanessa_lacayo@nps.gov>
CC:	"Kupper, Kathy" <kathy_kupper@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov>, Ryan McClymont <rmcclymont@usgs.gov>, Catherine Puckett <cpuckett@usgs.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Thank you for the call Vanessa, we really appreciate you letting us know. I could not find a clip either.

Feel free to forward news media inquiries directly to Dan (he knows our drill) and if possible include myself, Ryan McClymont (copied) and Catherine Puckett (copied) on the chain if possible.

Thank you,

Paul

Paul C. Laustsen
U.S. Geological Survey
Office of Communications
plaustsen@usgs.gov
650-847-8522

On Fri, Jun 7, 2019 at 1:24 PM Lacayo, Vanessa <vanessa_lacayo@nps.gov> wrote:

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Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

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Conversation Contents

Fwd: From NPS.gov: mike@dailycallernewsfoundation.org

"GLAC Questions, NPS" <glac_questions@nps.gov>

From:	"GLAC Questions, NPS" <glac_questions@nps.gov>
Sent:	Fri Jun 07 2019 14:31:22 GMT-0600 (MDT)
To:	Connie Stahr <connie_stahr@nps.gov>, Lauren Alley <lauren_alley@nps.gov>
Subject:	Fwd: From NPS.gov: mike@dailycallernewsfoundation.org

Hi Connie,

Here is another email requesting a comment about the signs discussing glaciers being gone by 2020 in the park. I have included Lauren on this email as well but did not respond to the emailer.

Please let me know if you have further questions.

Teagan Tomlin
Visitor Services Assistant
Glacier National Park
nps.gov/glac
facebook.com/GlacierNPS
twitter - @glaciernps
http://www.flickr.com/photos/glaciernps

---------- Forwarded message ---------
From: <no-reply@nps.gov>
Date: Fri, Jun 7, 2019 at 8:13 AM
Subject: From NPS.gov: mike@dailycallernewsfoundation.org
To: <glac_questions@nps.gov>

Email submitted from: mike@dailycallernewsfoundation.org at /glac/contacts.htm

Use mike@dailycallernewsfoundation.org to reply to this message
Mailing Address:
Michael C Bastasch
1920 L St NW #2
Suite 900
Washington, District Of Columbia 22203
United States

Hi, I was wondering if Glacier Park NP had any comment on replacing signs that warned glaciers would be "gone" by 2020? That claim was made in a recent blog post: https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc. Please let me know. Thanks!

"Stahr, Connie" <connie_stahr@nps.gov>

From:	"Stahr, Connie" <connie_stahr@nps.gov>
Sent:	Fri Jun 07 2019 14:36:48 GMT-0600 (MDT)
To:	"Tomlin, Teagan" <teagan_tomlin@nps.gov>
CC:	Lauren Alley <lauren_alley@nps.gov>
Subject:	Re: From NPS.gov: mike@dailycallernewsfoundation.org

Lauren, please let us know how to handle these comments which ask for a reply.

Thanks!

Connie Stahr
Executive Assistant
Office of the Superintendent
Glacier National Park
P.O. Box 128
West Glacier, MT 59936
406-888-7901 Phone
406-888-7904 Fax

On Fri, Jun 7, 2019 at 2:31 PM GLAC Questions, NPS <glac_questions@nps.gov> wrote:

Hi Connie,

Here is another email requesting a comment about the signs discussing glaciers being gone by 2020 in the park. I have included Lauren on this email as well but did not respond to the emailer.

Please let me know if you have further questions.

Teagan Tomlin
Visitor Services Assistant
Glacier National Park
nps.gov/glac
facebook.com/GlacierNPS
twitter - @glaciernps
http://www.flickr.com/photos/glaciernps

---------- Forwarded message ---------
From: <no-reply@nps.gov>

Date: Fri, Jun 7, 2019 at 8:13 AM
Subject: From NPS.gov: mike@dailycallernewsfoundation.org
To: <glac_questions@nps.gov>

Email submitted from: mike@dailycallernewsfoundation.org at /glac/contacts.htm

Use mike@dailycallernewsfoundation.org to reply to this message
Mailing Address:
Michael C Bastasch
1920 L St NW #2
Suite 900
Washington, District Of Columbia 22203
United States

Hi, I was wondering if Glacier Park NP had any comment on replacing signs that warned glaciers would be "gone" by 2020? That claim was made in a recent blog post: https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc. Please let me know. Thanks!

Conversation Contents

Possibly trending topic

"Abbey, Kristine" <kristine_abbey@nps.gov>

From:	"Abbey, Kristine" <kristine_abbey@nps.gov>
Sent:	Fri Jun 07 2019 08:24:52 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
Subject:	Possibly trending topic

This topic seems to be trending in a small way. Second time in two days it's come up in my Google search.

Might hit the mainstream...who knows.

https://legalinsurrection.com/2019/06/glacier-national-park-starts-removing-its-gone-by-2020-signs/

Kristine Abbey
Public Affairs Assistant
Glacier National Park
406-888-7895
Kristine_Abbey@nps.gov
Mailing: PO Box 128, West Glacier, MT 59936
Physical: Glacier National Park HQ, 64 Grinnell Dr., West Glacier, MT 59936

Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Fri Jun 07 2019 14:13:29 GMT-0600 (MDT)
To:	"Abbey, Kristine" <kristine_abbey@nps.gov>
Subject:	Re: Possibly trending topic

Thanks. This is supersizing. Please forward any media calls about this to my voicemail. We'll circle up on Monday.

Sent from my iPhone

On Jun 7, 2019, at 8:24 AM, Abbey, Kristine <kristine_abbey@nps.gov> wrote:

> This topic seems to be trending in a small way. Second time in two days it's come up in my Google search.

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https://legalinsurrection.com/2019/06/glacier-national-park-starts-removing-its-gone-by-2020-signs/

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Glacier National Park
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Kristine_Abbey@nps.gov
Mailing: PO Box 128, West Glacier, MT 59936
Physical: Glacier National Park HQ, 64 Grinnell Dr., West Glacier, MT 59936

"Abbey, Kristine" <kristine_abbey@nps.gov>

From:	"Abbey, Kristine" <kristine_abbey@nps.gov>
Sent:	Fri Jun 07 2019 14:26:12 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
Subject:	Re: Possibly trending topic

Got it.

I saw it posted another place as well. The reposters are feeding off the same source:

http://lysanderspooneruniversity.com/

https://www.youtube.com/watch?v=DfPKGqsy8Bo

Kristine Abbey
Public Affairs Assistant
Glacier National Park
406-888-7895
Kristine_Abbey@nps.gov
Mailing: PO Box 128, West Glacier, MT 59936
Physical: Glacier National Park HQ, 64 Grinnell Dr., West Glacier, MT 59936

On Fri, Jun 7, 2019 at 2:13 PM Lauren Alley <lauren_alley@nps.gov> wrote:

Thanks. This is supersizing. Please forward any media calls about this to my voicemail. We'll circle up on Monday.

Sent from my iPhone

On Jun 7, 2019, at 8:24 AM, Abbey, Kristine <kristine_abbey@nps.gov> wrote:

This topic seems to be trending in a small way. Second time in two days it's come up in my Google search.

Might hit the mainstream...who knows.

https://legalinsurrection.com/2019/06/glacier-national-park-starts-removing-its-gone-by-2020-signs/

Kristine Abbey
Public Affairs Assistant
Glacier National Park
406-888-7895
Kristine_Abbey@nps.gov
Mailing: PO Box 128, West Glacier, MT 59936
Physical: Glacier National Park HQ, 64 Grinnell Dr., West Glacier, MT 59936

Conversation Contents

Media Inquiry: [EXTERNAL] Is this true?

"Kupper, Kathy" <kathy_kupper@nps.gov>

From:	"Kupper, Kathy" <kathy_kupper@nps.gov>
Sent:	Thu Jun 06 2019 12:11:09 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>
Subject:	Media Inquiry: [EXTERNAL] Is this true?

Hi Lauren,

DOI received a media inquiry regarding the following article. Can you please let us know if the info in it is correct and/or any related background?
https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc

Thank you,
Kathy

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

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"Alley, Lauren" <lauren_alley@nps.gov>

From:	"Alley, Lauren" <lauren_alley@nps.gov>
Sent:	Thu Jun 06 2019 15:29:30 GMT-0600 (MDT)

To: "Kupper, Kathy" <kathy_kupper@nps.gov>

CC: Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>

Subject: Re: Media Inquiry: [EXTERNAL] Is this true?

Hi Kathy,

Thanks for sending this along. Let me work with USGS on a response. I want to ensure that what we're saying about how we're using their science is 100% accurate.

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

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"Alley, Lauren" <lauren_alley@nps.gov>

From: "Alley, Lauren" <lauren_alley@nps.gov>

Sent:	Thu Jun 06 2019 15:50:08 GMT-0600 (MDT)
To:	Jeff Mow <jeff_mow@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, "Carolin, Tara" <tara_carolin@nps.gov>, "Sladek, Melissa" <melissa_sladek@nps.gov>, "Peitzsch, Erich" <epeitzsch@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

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Lauren Alley
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Kathy Kupper <kathy_kupper@nps.gov>

From:	Kathy Kupper <kathy_kupper@nps.gov>
Sent:	Thu Jun 06 2019 15:51:22 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
CC:	Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Great! Thank you!

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> Hi Kathy,
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> Glacier National Park

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"Fagre, Daniel" <dan_fagre@usgs.gov>

From:	"Fagre, Daniel" <dan_fagre@usgs.gov>
Sent:	Thu Jun 06 2019 16:31:32 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
CC:	Jeff Mow <jeff_mow@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, "Carolin, Tara" <tara_carolin@nps.gov>, "Sladek, Melissa" <melissa_sladek@nps.gov>, "Peitzsch, Erich" <epeitzsch@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Hi Lauren,
Only one correction - "peer reviewed research on glacial retreat modeling" - we haven't done retreat modeling recently but have published papers on glacier retreat. Retreat modeling by other scientists on glaciers in Switzerland and Canada show similar time frames for glacier disappearance as your statement referencing 2030 to 2080 for GNP's glaciers.

Dan

On Thu, Jun 6, 2019 at 3:50 PM Alley, Lauren <lauren_alley@nps.gov> wrote:

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fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc

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--
****
Daniel B. Fagre, Ph.D.
USGS Northern Rocky Mountain Science Center
215 Mather Drive
Glacier National Park
West Glacier, MT 59936
Ph: 406-888-7922
Email: dan_fagre@usgs.gov
****

"Carolin, Tara" <tara_carolin@nps.gov>

From:	"Carolin, Tara" <tara_carolin@nps.gov>
Sent:	Thu Jun 06 2019 16:56:12 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
CC:	Jeff Mow <jeff_mow@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, "Sladek, Melissa" <melissa_sladek@nps.gov>, "Peitzsch, Erich" <epeitzsch@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

A few additional points you might choose from include:

A paper published in 2003 predicted that the glaciers in Glacier National Park would be gone by 2030, based on modeling that the glaciers would continue to melt at the same rate that they had over the previous decades.

Further research in the late 2000s revealed specific glaciers were melting even faster than the rate used in the 2003 model, which began predictions that at least some of the glaciers may be gone as early as 2020. (See page 80 of the linked article.)

Research on the glaciers has continued, demonstrating variability in the rate at which individual glaciers are melting though the overall declining trend continues. Recent data show reductions in size range from 9%-96%, averaging a 68% reduction in glacial area overall.

Tara Carolin, Director
Crown of the Continent Research Learning Center
Glacier National Park
406-888-7863
406-888-7903 (fax)
https://www.nps.gov/rlc/crown

Research Learning Centers increase the effectiveness and communication of science in national parks.

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"Alley, Lauren" <lauren_alley@nps.gov>

From:	"Alley, Lauren" <lauren_alley@nps.gov>
Sent:	Thu Jun 06 2019 18:08:42 GMT-0600 (MDT)
To:	"Kupper, Kathy" <kathy_kupper@nps.gov>
CC:	Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov> Tracy Ammerman <tracy_ammerman@nps.gov>, "Carolin, Tara"

BCC: <tara_carolin@nps.gov>

Subject: Re: Media Inquiry: [EXTERNAL] Is this true?

Kathy/all,

Please see below for some context. I'm copying USGS public affairs for the Northern Rockies (Sarah Beldin) and the lead USGS scientist (Dan Fagre) on this response in case you or DOI have any follow up questions for us.

Cheers,

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"Kupper, Kathy" <kathy_kupper@nps.gov>

From:	"Kupper, Kathy" <kathy_kupper@nps.gov>
Sent:	Fri Jun 07 2019 06:26:53 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
CC:	Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov>
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"Beldin, Sarah" <sbeldin@usgs.gov>

From:	"Beldin, Sarah" <sbeldin@usgs.gov>
Sent:	Fri Jun 07 2019 07:17:20 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
CC:	Daniel Fagre <dan_fagre@usgs.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Hello Lauren

Thanks for thinking to include me on this message. I am no longer working as PIO for USGS NOROCK in MT (I'm back with the USGS Oregon office), but honestly, if Dan is ok with this language, I would proceed.

Dan: please include our Western Region OCAP contact if you have any questions about this (Ryan McClymont).

Thanks again,
Sarah

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--
Sarah Beldin
U.S. Geological Survey
FRESC Outreach Biologist
sbeldin@usgs.gov
541.750.1046

"Carolin, Tara" <tara_carolin@nps.gov>

From:	"Carolin, Tara" <tara_carolin@nps.gov>
Sent:	Fri Jun 07 2019 13:54:05 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, "Mow, Jeff" <jeff_mow@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, erich peitzsch <epeitzsch@usgs.gov>, Melissa Sladek <melissa_sladek@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Teagan at the front desk is getting numerous angry calls (yelling and violent swearing) over this article today. She contacted our office since almost all of you are out today. I forwarded her Lauren's email with information she can use and and also told her she could just take names for later response.

We may need to develop a more proactive response...

Tara Carolin, Director
Crown of the Continent Research Learning Center
Glacier National Park
406-888-7863
406-888-7903 (fax)
https://www.nps.gov/rlc/crown

Research Learning Centers increase the effectiveness and communication of science in national parks.

On Thu, Jun 6, 2019 at 6:08 PM Alley, Lauren <lauren_alley@nps.gov> wrote:

Kathy/all,

Please see below for some context. I'm copying USGS public affairs for the Northern Rockies (Sarah Beldin) and the lead USGS scientist (Dan Fagre) on this response in case you or DOI have any follow up questions for us.

Cheers,

Lauren

The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.

USGS regularly publicizes their research efforts. The National Park Service does not typically issue press releases for new interpretive displays or park signage.

A paper published in 2003 predicted that the glaciers in Glacier National Park would be gone by 2030, based on modeling that the glaciers would continue to melt at the same rate that they had over the previous decades.

Further research in the late 2000s revealed specific glaciers were melting even faster than the rate used in the 2003 model, which began predictions that at least some of the glaciers may be gone as early as 2020. (See page 80 of the linked article.)

Research on the glaciers has continued. In the last several years, USGS has released peer reviewed research on glacial retreat that provide greater accuracy than was available early on in the research project, including improved satellite images and a greater understanding of how site specific conditions affect glacier size and melt rate. The research shows variability in the rate at which individual glaciers are melting though the overall declining trend continues. Recent data show reductions in size range from 9%-96%, averaging a 68% reduction in glacial area overall.

The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.

In the past three years, the park has used the following statement when responding to the multiple media requests it receives about glacial retreat:

"There are currently 26 glaciers in the park. Scientific models project that many will no longer meet the size criteria used to define a glacier sometime between 2030 and 2080."

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

On Thu, Jun 6, 2019 at 12:11 PM Kupper, Kathy <kathy_kupper@nps.gov> wrote:

Hi Lauren,

DOI received a media inquiry regarding the following article. Can you please let us know if the info in it is correct and/or any related background?
https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc

Thank you,
Kathy

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

The National Park Service cares for special places saved by the American people so that all may experience our heritage.

EXPERIENCE YOUR AMERICA ®

Conversation Contents

From NPS.gov: Park Messaging

no-reply@nps.gov

From:	no-reply@nps.gov
Sent:	Fri Jun 07 2019 13:27:52 GMT-0600 (MDT)
To:	lauren_alley@nps.gov
Subject:	From NPS.gov: Park Messaging

Email submitted from: (b) (6) [redacted]@outlook.com at /glac/learn/news/contactpublicaffairs.htm

Use (b) (6) [redacted]@outlook.com to reply to this message

Hi - there is some information on social media saying that the park is "quietly" changing its messaging about glaciers. Here's an example: "Officials at Glacier National Park (GNP) have begun quietly removing and altering signs and government literature which told visitors that the Park's glaciers were all expected to disappear by either 2020 or 2030." - Roger Roots, J.D., Ph.D., Founder, Lysander Spooner University. Can you advise if that is true? Thank you.

Conversation Contents

Fwd: Media Inquiry: [EXTERNAL] Is this true?

Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Thu Jun 06 2019 13:13:47 GMT-0600 (MDT)
To:	tracy_ammerman@nps.gov
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

Tracy- do you have anything to add? Assume that we are updating interpretive material and have been for several years to reflect latest USGS models.

Sent from my iPhone

Begin forwarded message:

From: "Kupper, Kathy" <kathy_kupper@nps.gov>
Date: June 6, 2019 at 12:11:09 PM MDT
To: "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>
Subject: Media Inquiry: [EXTERNAL] Is this true?

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https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc

Thank you,
Kathy

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

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EXPERIENCE YOUR AMERICA ®

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Thu Jun 06 2019 13:31:46 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Lauren,

Yes, we are indeed updating our interpretive information/exhibits based on emerging information from USGS. There was nothing covert or sneaky about it, but simply an effort to try to have more accurate information in place before the SMVC opened to the public this year. The park's position (based on scientific evidence) is still that our glaciers are shrinking and disappearing and that there is typically a net loss of mass "at the end of the year." The prediction that they would be gone by 2020 appears to have been an inaccurate estimate based on the models used at that time, but there is absolutely no disagreement in the scientific community that they will disappear in the not-too-distant future. GLAC is removing specific dates and using more general language, as we (and USGS) have realized that although the trend is evident, citing a specific date was perhaps presumptive.

I hope this helps. I am happy to chat with you more if you'd like. Of course, discussion with Dan Fagre and/or Caitlyn Florentine might be useful, as well.

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930

On Thu, Jun 6, 2019 at 1:13 PM Lauren Alley <lauren_alley@nps.gov> wrote:

> Tracy- do you have anything to add? Assume that we are updating interpretive material and have been for several years to reflect latest USGS models.
>
> Sent from my iPhone
>
> Begin forwarded message:
>
> > **From:** "Kupper, Kathy" <kathy_kupper@nps.gov>
> > **Date:** June 6, 2019 at 12:11:09 PM MDT
> > **To:** "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon
~~~~~~~~~~~~~~~~~~~~~~~~~

<marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>
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Thank you,
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Conversation Contents

Re: Climate Change Brochure

"Sladek, Melissa" <melissa_sladek@nps.gov>

From:	"Sladek, Melissa" <melissa_sladek@nps.gov>
Sent:	Wed Oct 24 2018 10:50:01 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tara Carolin <Tara_Carolin@nps.gov>, William Hayden <Bill_Hayden@nps.gov>
Subject:	Re: Climate Change Brochure

Hi Daniel,

Hey, just to let you and Teagan know, we still have two and a half boxes of climate change brochures over here. The CCRLC also got a grant from the Conservancy to print these so once they are gone, the CCRLC does not have any more money for them.

This product was developed in close collaboration with Dan, Lisa, and Bill. Tara and I would like to get together with you and discuss a plan to move forward.

Melissa Sladek
Science Communication Specialist
Crown of the Continent Research Learning Center
Glacier National Park
P.O. Box 128
West Glacier, MT 59936
406-888-7894

On Tue, Oct 23, 2018 at 5:10 PM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> Hey Melissa,
>
> Teagan and I have been developing a publications plan for the park over the past few weeks. It's come up that we should redo the climate change brochure. I believe you developed the last edition?
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> Because it's something I'm passionate about I'd love to help work on a new version. One of the projects I'm most proud of ever working on is the wayside exhibit duo at Jackson Glacier Overlook. Changing with the Times and Losing a Namesake
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> I've been sketching out some mock ups of an A3 or A4 double sided handout brochure that uses the wayside exhibit graphics and text but expands a little into some wildlife impacts as well.
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> What do you think of all this? Maybe late next week we could get together and I can show you what I'm working on?
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> -daniel

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Thu Oct 25 2018 11:05:42 GMT-0600 (MDT)
To:	"Sladek, Melissa" <melissa_sladek@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tara Carolin <Tara_Carolin@nps.gov>
Subject:	Re: Climate Change Brochure

Melissa/Tara

What are you considering as a next step for climate change communications? It seems that this existing brochure needs some updating, but without funding we should think about how we proceed. There is a possibility to do something in the summer newspaper and maybe weave a brochure of some kind into the GNPC printing donation. It depends on how much I can stretch the budget and if there are new, unplanned Howe Ridge Fire communication products that are needed.

I think we have an opportunity now to provide something that could be more interpretive and also a more in-depth product similar to the existing one. We should get together and explore options.

Daniel will be gone soon. Maybe we can get together before he leaves on furlough.

On Wed, Oct 24, 2018 at 10:50 AM Sladek, Melissa <melissa_sladek@nps.gov> wrote:

> Hi Daniel,
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> -daniel

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Carolin, Tara" <tara_carolin@nps.gov>

From:	"Carolin, Tara" <tara_carolin@nps.gov>
Sent:	Tue Oct 30 2018 16:57:41 GMT-0600 (MDT)
To:	Bill Hayden <bill_hayden@nps.gov>
CC:	Melissa Sladek <melissa_sladek@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>
Subject:	Re: Climate Change Brochure

Yes, I agree we need to get together and discuss the best strategy as to how we should work together on climate change communication, which has always been one of our special emphasis topics at the CCRLC. We are working on several types of products we can share with you along with some lessons learned from the current brochure.

Would you all be available Thurs at 3:30pm?

Tara Carolin, Director
Crown of the Continent Research Learning Center
Glacier National Park
406-888-7863
406-888-7903 (fax)
https://www.nps.gov/rlc/crown

Research Learning Centers increase the effectiveness and communication of science in national parks.

On Thu, Oct 25, 2018 at 11:05 AM Hayden, William <bill_hayden@nps.gov> wrote:

> Melissa/Tara
>
> What are you considering as a next step for climate change communications? It seems that this existing brochure needs some updating, but without funding we should think about how we proceed. There is a possibility to do something in the summer newspaper and maybe weave a brochure of some kind into the GNPC printing donation. It depends on how much I can stretch the budget and if there are new, unplanned Howe Ridge Fire communication products that are needed.
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> On Wed, Oct 24, 2018 at 10:50 AM Sladek, Melissa <melissa_sladek@nps.gov> wrote:
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>> West Glacier, MT 59936
>> 406-888-7894
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--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Fri Nov 02 2018 14:10:33 GMT-0600 (MDT)
To:	Tara Carolin <tara_carolin@nps.gov>
CC:	"Sladek, Melissa" <melissa_sladek@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>
Subject:	Re: Climate Change Brochure

Hummm, this slipped by if you were talking about last Thursday. What other date this coming week might work for you?

On Tue, Oct 30, 2018 at 4:57 PM Carolin, Tara <tara_carolin@nps.gov> wrote:

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On Thu, Oct 25, 2018 at 11:05 AM Hayden, William <bill_hayden@nps.gov> wrote:

Melissa/Tara

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On Wed, Oct 24, 2018 at 10:50 AM Sladek, Melissa <melissa_sladek@nps.gov> wrote:

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Melissa Sladek
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Crown of the Continent Research Learning Center
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On Tue, Oct 23, 2018 at 5:10 PM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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> > --
> > **Bill Hayden**
> > Interpretive Specialist
> > Glacier National Park
> > West Glacier, MT 59936
> > 406-888-7927

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
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"Sladek, Melissa" <melissa_sladek@nps.gov>

From:	"Sladek, Melissa" <melissa_sladek@nps.gov>
Sent:	Fri Nov 02 2018 14:54:53 GMT-0600 (MDT)
To:	"Hayden, William" <bill_hayden@nps.gov>
CC:	Tara Carolin <tara_carolin@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>
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Hi there. Tara and I are both available next Wednesday afternoon or most of the day on Thursday.

Thanks.

Melissa Sladek
Science Communication Specialist
Crown of the Continent Research Learning Center
Glacier National Park
P.O. Box 128
West Glacier, MT 59936
406-888-7894

On Fri, Nov 2, 2018 at 2:10 PM, Hayden, William <bill_hayden@nps.gov> wrote:

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406-888-7894

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Bill Hayden
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--
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406-888-7927

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent: Thu Nov 08 2018 11:22:58 GMT-0700 (MST)

To: William Hayden <bill_hayden@nps.gov>
Subject: Fwd: Climate Change Brochure

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From: **Sladek, Melissa** <melissa_sladek@nps.gov>
Date: Fri, Nov 2, 2018 at 2:54 PM
Subject: Re: Climate Change Brochure
To: Hayden, William <bill_hayden@nps.gov>
Cc: Tara Carolin <tara_carolin@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>

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Melissa Sladek
Science Communication Specialist
Crown of the Continent Research Learning Center
Glacier National Park
P.O. Box 128
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406-888-7894

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Daniel Lombardi
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"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Thu Nov 08 2018 13:26:52 GMT-0700 (MST)
To:	Daniel Lombardi <daniel_lombardi@nps.gov>, "Sladek, Melissa" <melissa_sladek@nps.gov>, Tara Carolin <Tara_Carolin@nps.gov>
Subject:	Re: Climate Change Brochure

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From:	"Sladek, Melissa" <melissa_sladek@nps.gov>
Sent:	Thu Nov 08 2018 15:19:37 GMT-0700 (MST)
To:	"Hayden, William" <bill_hayden@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>, Tara Carolin <Tara_Carolin@nps.gov>
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Sent:	Thu Nov 08 2018 15:57:28 GMT-0700 (MST)
To:	"Sladek, Melissa" <melissa_sladek@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>, Tara Carolin <Tara_Carolin@nps.gov>
Subject:	Re: Climate Change Brochure

OK let's look at scheduling this again in later January.

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Conversation Contents

Wayside Exhibit Projects

Attachments:

/1. Wayside Exhibit Projects/1.1 waysides for jeff.docx

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Tue Jun 11 2019 13:33:22 GMT-0600 (MDT)
To:	Connie Stahr <connie_stahr@nps.gov>
CC:	Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Wayside Exhibit Projects
Attachments:	waysides for jeff.docx

Attached is a brief outline of ongoing and upcoming exhibit projects around the park. I have listed the PMIS numbers for the ones that are included in SCC proposals.

This list does not include all exhibits and does not include interior exhibits in the visitor centers. That list will take more time to generate.

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"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Wed Jun 19 2019 14:35:20 GMT-0600 (MDT)
To:	"Hayden, William" <bill_hayden@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: Wayside Exhibit Projects

Thanks, Bill!

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
~~~~~~~~~~~~~~~~~~~~~~~~~~

406-888-7930

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Rehabilitate Many Glacier Waysides – 11 wayside exhibits

PMIS Project 238642 – scheduled for 2020

In 2016 we submitted a PMIS proposal to update and repair the Many Glacier Wayside Exhibits. They were installed is 2014 and 2015. This is a cyclic maintenance proposal. In addition to repair and rehab of bases the content will be reviewed for needed resource and safety updates. The exhibits cover a broad range of subjects from hydrological features, wildlife habitat, cultural history and visitation patterns, and how glaciers function, their impact on the parks geography, and their rate of melting. In these exhibits there is one bit of information that should be changed regarding glaciers. A sentence states that the glaciers will be gone in our lifetime. Depending on who is reading that exhibit, we should probably change that to may be gone.

In addition to these 11 waysides there are seven exhibit panels on the accessible portion of the Swiftcurrent Nature Trail and 7 trailhead panels at the beginnings of trails. One of the exhibit panels on the Swiftcurrent Nature Trail says that Scientists predict the park's alpine glaciers will vanish in the near future.

Rehabilitate Going-to-the-Sun Road West Side Waysides – 18 wayside exhibits

PMIS Project 239034 – scheduled for 2021

In 2016 we submitted a PMIS proposal to update and repair wayside exhibits along the west side of the Going-to-The-Sun Road. This is a cyclic maintenance proposal. Bases and frames will be repaired and/or replaced and exhibit content will be reviewed and changed as needed. As in other areas the exhibits speak to a broad range of topics and are mostly site specific to the view in that particular location.

One exhibit that should probably change sooner than 2021 is just south of the lodge. It is about the 2003 Howe Ridge Fire. Although the content is correct, it does not address that there was a fire in that same location in 2018. Visitors could be left with the impression that what they are looking at is all from 2003. Some of it is and some is from 2018.

Two of the exhibits directly address glaciers but they primarily discuss the carving done by the historic glaciers and not the current smaller ones. These two exhibits talk about melting but do not include any dates.

Review of this set of exhibits will be conducted to ensure that content still contains the most recent research findings and information.

In addition to these waysides there are nine exhibit panels along the Trail of the Cedars and five trailhead panels along this portion of the Going-to-the-Sun Road.

Rehabilitate Going-to-the-Sun Road East Side Waysides – 7 wayside exhibits

PMIS Project 257141 – scheduled for 2023

In 2018 we submitted a PMIS proposal to update and repair wayside exhibits along the west side of the Going-to-The-Sun Road. This is a cyclic maintenance proposal. Bases and frames will be repaired and/or replaced and exhibit content will be reviewed and changed as needed.

As a group these exhibits have climate change messages more than other areas of the park. None of them have dates associated with them. Two of them directly address climate change and glacial retreat (Jackson Glacier Overlook). The Triple Divide and St. Mary River waysides include statements that question how a changing climate will affect the park and water availability downstream.

In addition there are trailhead panels at 5 locations.

Rehabilitate Logan Pass Waysides – 20 wayside exhibits

PMIS Project 257143 – scheduled for 2024

In 2018 we submitted a PMIS proposal to update and repair wayside exhibits along the west side of the Going-to-The-Sun Road. This is a cyclic maintenance proposal. Bases and frames will be repaired and/or replaced and exhibit content will be reviewed and changed as needed. The exhibits at Logan Pass focus on wildlife and plant adaptations to the sub-alpine environment and geologic history. Two of the exhibits at Logan Pass currently have dates for when the glaciers will be gone that are no longer consistent with recent research findings. These two panels should be changed. We should not wait until the entire project is funded to complete these revisions.

Rehabilitate North Fork Waysides – 20 wayside exhibits

PMIS Project 237853

We are currently working to revise, repair, and rehabilitate wayside exhibits in the North Fork/Camas Road area and locations in Apgar and West Glacier. This set of exhibits highlight cultural history on the west side of the park, fire history, wildlife, and recreational opportunities. To a large extent climate change messages are not included in these exhibits. We are looking to revise language that exists on the waysides in place now and we are changing some topics to make planning recreational activities easier and safer. Our fire messages will highlight recent activity in the park and make those exhibits reflect current conditions.

Two Medicine Wayside Exhibits. – 14 wayside exhibits

Within the last year we updated exhibits in the Two Medicine Valley. Exhibits on native plant uses have been designed and are awaiting tribal consultation. There is a new exhibit by the Campstore. It replaces the old exhibit about the chalet system parkwide and replaces it with an exhibit specific to the Campstore building and its history as a part of the Two Medicine Chalets. A replacement exhibit was

placed at the Two Medicine Train Depot updating the connection that trains played in the development of the park. There is an exhibit on the history of the building of the Glacier Park Lodge that replaced an older exhibit on the red buses. Once Glacier Park Inc. lost the contract for the park they were no longer associated with the red buses. Rather than remove the exhibit altogether it was replaced with an exhibit that highlighted the building of the hotel and the connection with the Great Northern. In the future a decision could be made to remove this exhibit entirely. We have not had those discussion as of yet.

There are two trailhead panels in the Two Medicine Valley.

Other Exhibits

Additional PMIS projects are in the system to rehabilitate and replace trailhead panels throughout the park…a multi year proposal, and to redo exhibits at Goat Haunt. Both projects were moved to later years in the comp plan.

This summer we are finishing work on Sun Point exhibits (12 panels), continuing work on exhibits about the Salish/Kootenai, updating LEEDs signs at the Apgar Visitor Center, a historic walking tour for HQ, and an exhibit on Mission 66 to mitigate an adverse effect on the restroom in the Apgar Campground.

There is a proposal in the system to rehabilitate the exhibits at the St. Mary Visitor Center. It is PMIS #257367. It is a multi-year Rec Fee project and was moved back in the comp plan earlier this year.

Conversation Contents

If visitors ask when the glaciers will be gone:

Attachments:

/2. If visitors ask when the glaciers will be gone:/1.1 STMARY-VC-EXHIBIT-1-OLD.png
/2. If visitors ask when the glaciers will be gone:/1.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/2. If visitors ask when the glaciers will be gone:/1.3 STMARY-VC-EXHIBIT-2-OLD.png
/2. If visitors ask when the glaciers will be gone:/1.4 STMARY-VC-EXHIBIT-2-UPDATED.png
/2. If visitors ask when the glaciers will be gone:/2.1 STMARY-VC-EXHIBIT-1-OLD.png
/2. If visitors ask when the glaciers will be gone:/2.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/2. If visitors ask when the glaciers will be gone:/2.3 STMARY-VC-EXHIBIT-2-OLD.png
/2. If visitors ask when the glaciers will be gone:/2.4 STMARY-VC-EXHIBIT-2-UPDATED.png

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Fri Jun 14 2019 11:49:40 GMT-0600 (MDT)
To:	Marc Neidig <marc_neidig@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>
CC:	William Hayden <bill_hayden@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>
Subject:	If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

If visitors ask when the glaciers will be gone:
Data show that in 1966, the park had 35 named glaciers large enough to be considered active. By 2015, only 26 named glaciers remained in that category. The average area reduction was 39 percent, though some lost as much as 85 percent. This trend of glacier retreat is expected to continue as temperatures rise. Some small remnant ice may persist late into the 21st century or even beyond, depending on future rates of climate change.

These updated webpages are your best secondary sources for information on the park's glaciers:

- https://www.nps.gov/glac/learn/nature/melting-glaciers.htm
- https://www.nps.gov/glac/learn/nature/how-to-see-a-glacier.htm
- https://www.nps.gov/glac/learn/nature/glacial-geology.htm

Background on previously used prediction dates:
A USGS geospatial model published in a 2003 paper predicted that Blackfoot and Jackson would be gone by 2030. Because these are two of the larger glaciers in the park (2nd and 6th respectively in 1966), it was extrapolated that if they were gone, the rest of the glaciers in the park would be gone too. The predicted date of 2030 was put on several exhibits throughout the park, including in the Apgar and St. Mary Visitor Center plazas.

Further research in the late 2000s (page 80) revealed that Jackson and Blackfoot glaciers were melting even faster than the rate predicted in the 2003 geospatial model. So fast, in fact, that if the rate continued they would be gone by 2020. It was then extrapolated that if Blackfoot and Jackson were gone by 2020, the rest of the glaciers in the park would be gone too. The 2020 date was then put on two exhibits outside the Logan Pass Visitor Center and on two exhibits inside the St. Mary Visitor Center (see below).

In May, 2019 the St. Mary Visitor Center exhibits were updated to reflect the analyses, data, and insights that have emerged since 2010. This latest research shows shrinking of all the park's glaciers but in ways far more complicated, and interesting, than expressed in the early 2000s. In the three places that used the 2020 date, the exhibits now say: *"Future Generations;" "When they will completely disappear, however, depends on how and when we act;"* and *"Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking."* (See images below.)

There are plans to update all the other exhibits (at the Logan Pass, Apgar, and St. Mary visitor centers) that use the 2020 and 2030 dates as time and funding allows.

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STMARY-VC-EXHIBIT-2-OLD.png

STMARY-VC-EXHIBIT-2-UPDATED.png

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Fri Jun 14 2019 11:57:02 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

Thanks for pulling this together.

On Fri, Jun 14, 2019 at 11:50 AM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> **If visitors ask when the glaciers will be gone:**
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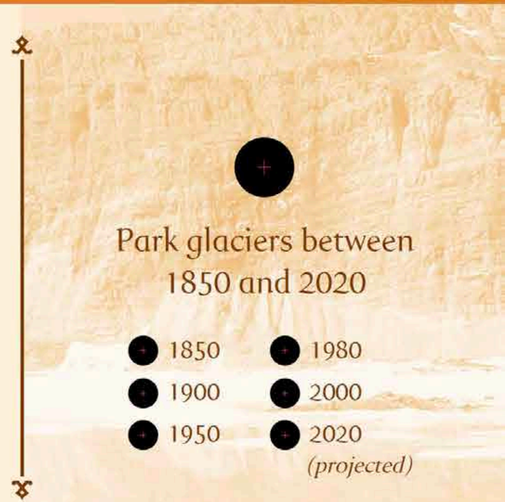
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

GOODBYE TO THE GLACIERS

The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. They are now rapidly shrinking due to human-caused climate change. Computer models indicate the glaciers will all be gone by the year 2020.

Glacier National Park was named for the sculpting actions of the Pleistocene glaciers that covered this landscape 12,000 to 130,000 years ago.



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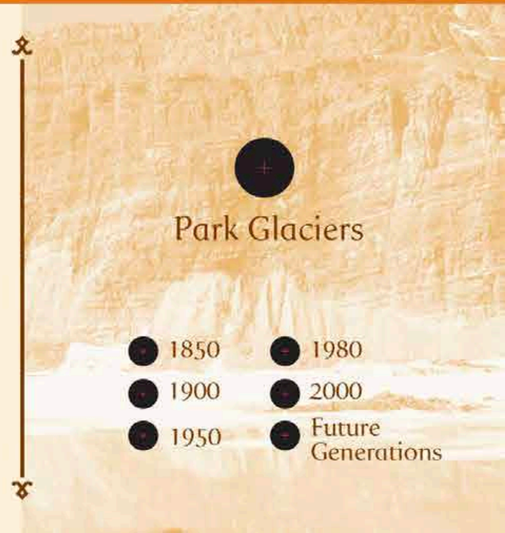
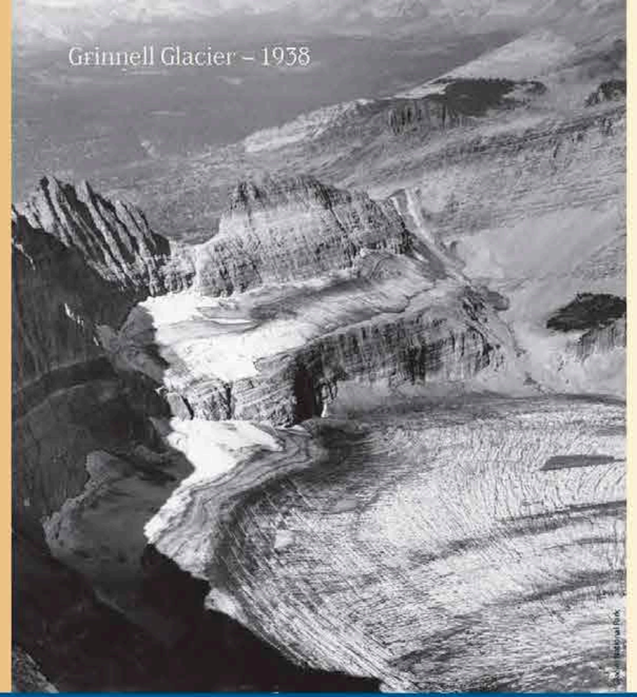
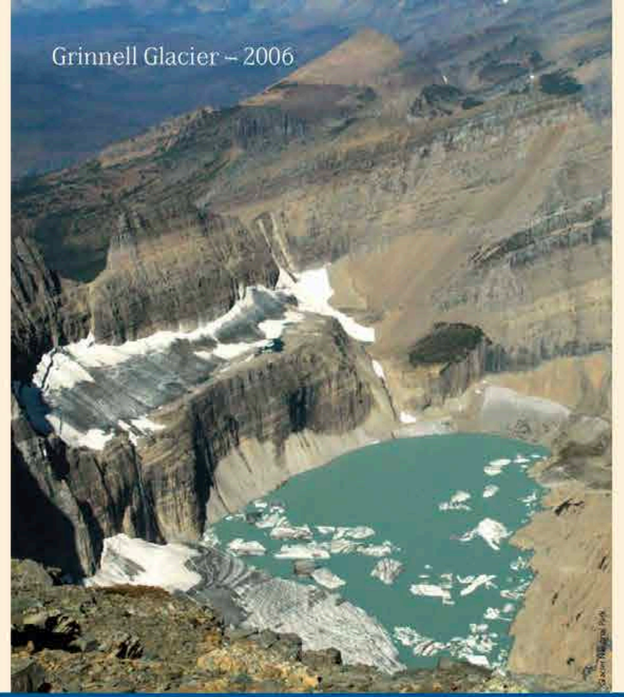


Glaciers are moving masses of ice. The glaciers that shaped the park were massive. During the pleistocene—12,000–130,000 years ago—the glaciers covering this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

In 1850 there were 150 glaciers in the park; in 2010 the number decreased to 25. Current climate models suggest that all of the glaciers in Glacier National Park will be gone by 2020.

Grinnell Glacier, located high in the Many Glacier valley, has significantly retreated in recent decades.

GLACIERS ON THE MOVE

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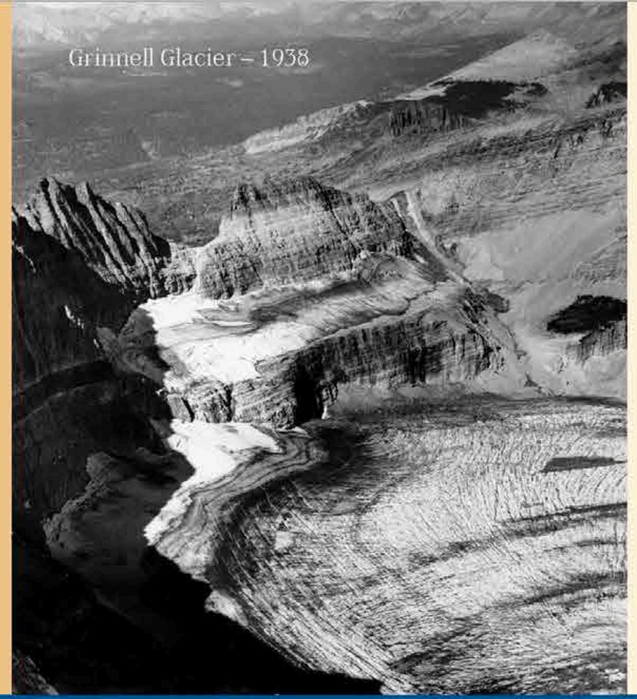

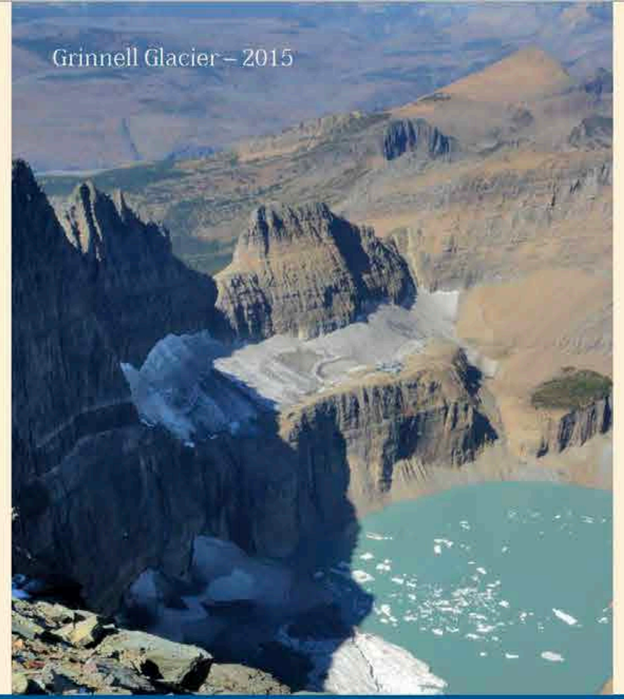

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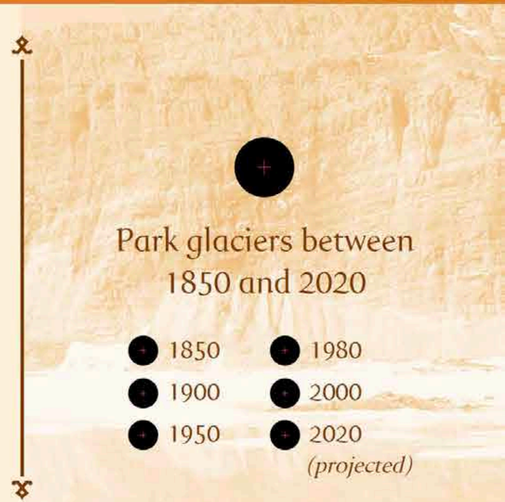

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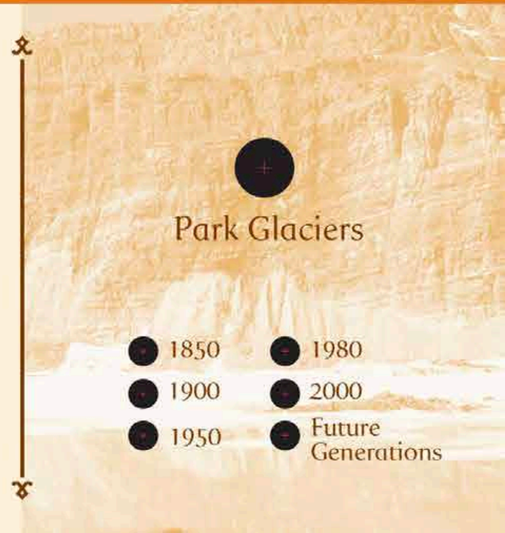

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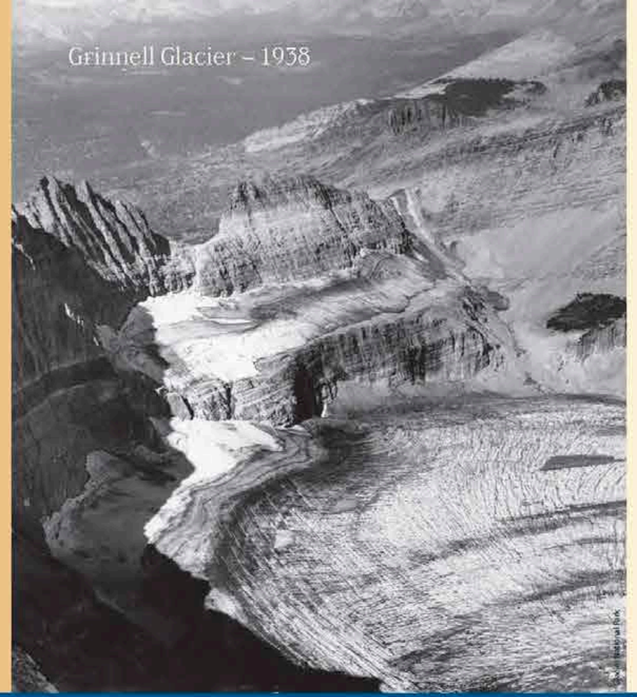

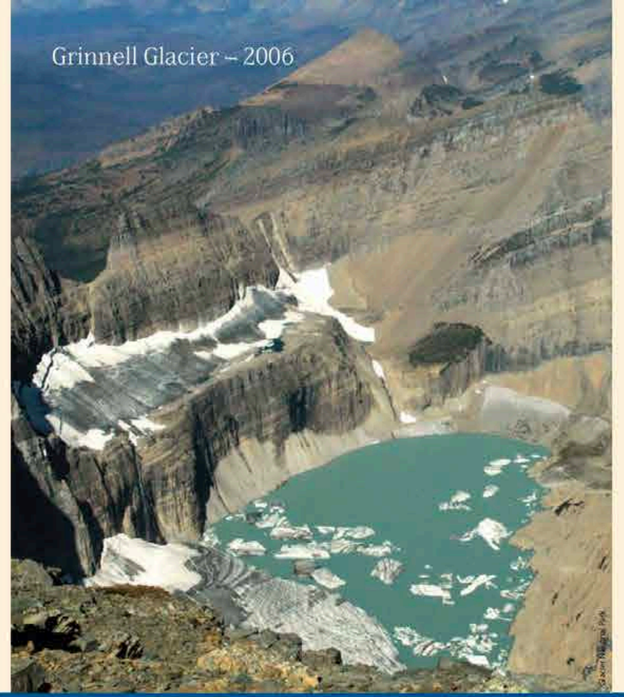

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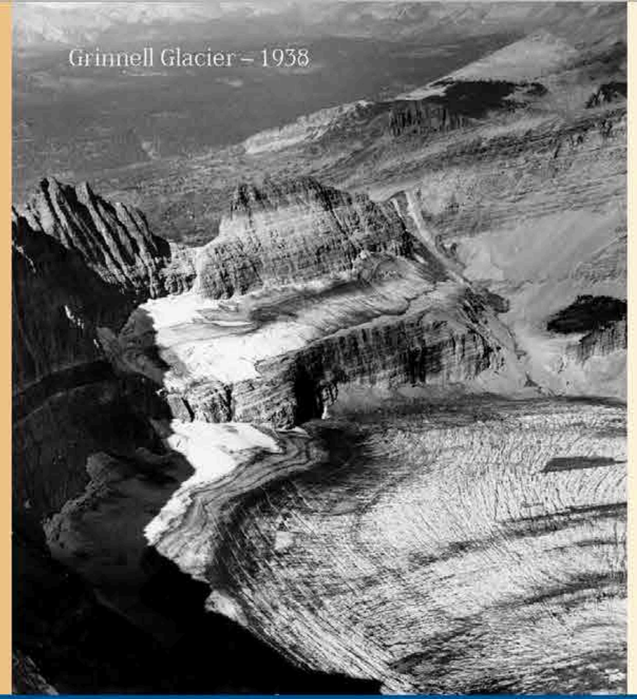

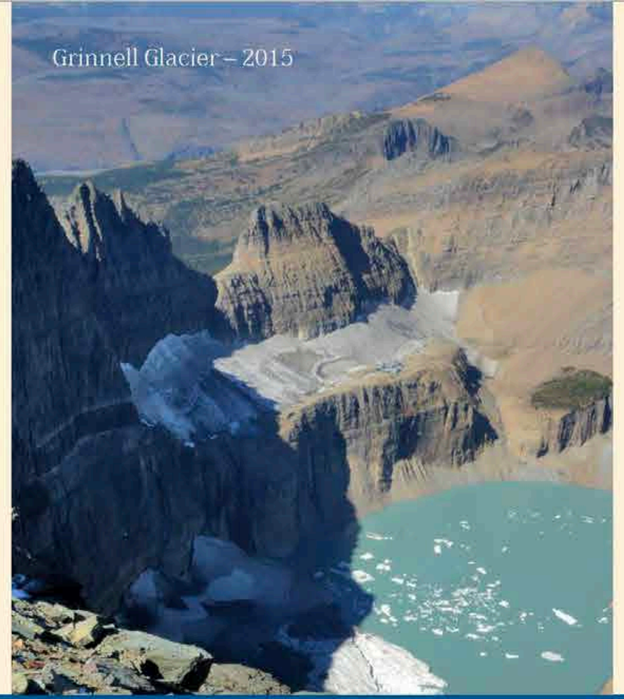

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GLACIERS ON THE MOVE

Conversation Contents

Exhibit text and/or photos ASAP?

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Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Sat Jun 08 2019 15:05:54 GMT-0600 (MDT)
To:	lee_rademaker@nps.gov, debby_smith@nps.gov
CC:	Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject:	Exhibit text and/or photos ASAP?

Hey Lee and Debby - Are either of you working today or tomorrow? There are some media outlets reporting about our Glacier exhibit updates and I'd like to get a sense of how things looked before and after so we can put some info on the web if needed to clear up confusion. My guess is that by Monday morning, main stream media will be calling. If you have text or photos or anything, I would really appreciate it. Cc to Tracy and Bill as well. Thanks all. Sent from my iPad

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Sat Jun 08 2019 16:20:37 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, "Mensch, D" <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Here are some attachments and some background.

The exhibits in the St. Mary Visitor Center were probably installed in 2010. There had been several planning and design meetings with Harpers Ferry Center personnel in the several years

previous. Mark Wagner was the lead on the exhibit redesigns. Sheri Forbes was the Chief of Interpretation. I was actually not involved in any aspect of the project or meetings from start to finish, so my memory on the exact dates is fuzzy. My guess on the year is based on the final planning document from the fabricator of the exhibits. The planning and design most surely happened much prior to that date. Mark Wagner may know more specifics.

In any case the exhibits that deal with glacial retreat were based on the USGS information that was available at that time. Since then their research has continued and evolved to include a more refined picture of glaciers in the park. Like much of scientific research, there are often not concrete black and white answers to basic questions, and that is often hard for some people to grapple with.

In the late summer, or fall, of 2017 staff from the USGS informed us, the media staff, that there were dates in the exhibits near the relief map at St. Mary that were not consistent with current research and asked that we change them. We were unable to do that for the 2018 season. At the end of the season we removed the exhibits and made changes to the original files. Those changes went through review by NPS and USGS staff and our sign shop was able to fabricate them and have them installed just prior to the opening of the Visitor Center this spring. Attached you should find the new exhibits and the former exhibits as PDF files.

There are also exhibits at the Apgar and St. Mary Visitor Center plazas, outside, that have dates that need changing. Those exhibits date from 2007. There are two exhibits that I know of at Logan Pass that likewise have these dates and should be changed out. In 2018 two new glacier exhibits replaced the one exhibit at Jackson Glacier Overlook. The old one had the 2030 date on it as well. It also contained images from the computer projection model, that was based on USGS work published in the early 2000s, I think 2003. This oldexhibit was designed in 2006 in coordination with Leigh Welling, who was in charge of the Crown of the Continent Research Learning Center at the time. I remember the date because I worked on refining her files while I was in Seattle that entire summer. She went from Glacier to a position in Colorado for the Natural Resources Division, where she dealt specifically with climate change issues.

A more complete review of other wayside exhibits will show mentions of climate change and some may have dates, although none come to mind at the moment. I can provide copies of these other exhibits if you wish, but I don't want to overload this particular email. We have them to view when needed.

Exhibit GL-07-400 May 2019 Revisions.pdf is the exhibit at the relief map that has the button to push for locations of the glaciers. It does not mention a specific date for the complete glacial melt. GL-07-400rev2.pdf is the original file as installed when the rest of the exhibits went in.

Exhibit GL-06-300rev1.pdf is the as installed original exhibit that is in front of one of the windows looking out at the mountains. It mentions also that 202 is the year the glaciers will be melted. GL-06-300 updated MAY 2019.pdf is the new file that was installed last month.

Daniel/Tracy feel free to provide any details or updates that I may have missed or gotten wrong.

On Sat, Jun 8, 2019 at 3:05 PM Lauren Alley <lauren_alley@nps.gov> wrote:

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>
> Are either of you working today or tomorrow?
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--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Mon Jun 10 2019 08:00:57 GMT-0600 (MDT)
To:	"Mow, Jeff" <jeff_mow@nps.gov>, Connie Stahr <connie_stahr@nps.gov>
CC:	"Alley, Lauren" <lauren_alley@nps.gov>, Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Fwd: Exhibit text and/or photos ASAP?
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Jeff,

For our discussion and your information. If we need additional detail in regard to timing, I could reach out to Mark Wagner and/or HFC.

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930

---------- Forwarded message ---------
From: **Hayden, William** <bill_hayden@nps.gov>
Date: Sat, Jun 8, 2019 at 4:20 PM
Subject: Re: Exhibit text and/or photos ASAP?
~~~~~~~~~~~~~~~~~~~~~~~~~

To: Lauren Alley <lauren_alley@nps.gov>
Cc: Lee Rademaker <lee_rademaker@nps.gov>, Mensch, D <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>

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In any case the exhibits that deal with glacial retreat were based on the USGS information that was available at that time. Since then their research has continued and evolved to include a more refined picture of glaciers in the park. Like much of scientific research, there are often not concrete black and white answers to basic questions, and that is often hard for some people to grapple with.

In the late summer, or fall, of 2017 staff from the USGS informed us, the media staff, that there were dates in the exhibits near the relief map at St. Mary that were not consistent with current research and asked that we change them. We were unable to do that for the 2018 season. At the end of the season we removed the exhibits and made changes to the original files. Those changes went through review by NPS and USGS staff and our sign shop was able to fabricate them and have them installed just prior to the opening of the Visitor Center this spring. Attached you should find the new exhibits and the former exhibits as PDF files.

There are also exhibits at the Apgar and St. Mary Visitor Center plazas, outside, that have dates that need changing. Those exhibits date from 2007. There are two exhibits that I know of at Logan Pass that likewise have these dates and should be changed out. In 2018 two new glacier exhibits replaced the one exhibit at Jackson Glacier Overlook. The old one had the 2030 date on it as well. It also contained images from the computer projection model, that was based on USGS work published in the early 2000s, I think 2003. This oldexhibit was designed in 2006 in coordination with Leigh Welling, who was in charge of the Crown of the Continent Research Learning Center at the time. I remember the date because I worked on refining her files while I was in Seattle that entire summer. She went from Glacier to a position in Colorado for the Natural Resources Division, where she dealt specifically with climate change issues.

A more complete review of other wayside exhibits will show mentions of climate change and some may have dates, although none come to mind at the moment. I can provide copies of these other exhibits if you wish, but I don't want to overload this particular email. We have them to view when needed.

Exhibit GL-07-400 May 2019 Revisions.pdf is the exhibit at the relief map that has the button to push for locations of the glaciers. It does not mention a specific date for the complete glacial melt. GL-07-400rev2.pdf is the original file as installed when the rest of the exhibits went in.

Exhibit GL-06-300rev1.pdf is the as installed original exhibit that is in front of one of the windows looking out at the mountains. It mentions also that 202 is the year the glaciers will be melted. GL-06-300 updated MAY 2019.pdf is the new file that was installed last month.

Daniel/Tracy feel free to provide any details or updates that I may have missed or gotten wrong.

On Sat, Jun 8, 2019 at 3:05 PM Lauren Alley <lauren_alley@nps.gov> wrote:

> Hey Lee and Debby -
>
> Are either of you working today or tomorrow?
>
> There are some media outlets reporting about our Glacier exhibit updates and I'd like to get a sense of how things looked before and after so we can put some info on the web if needed to clear up confusion.
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> My guess is that by Monday morning, main stream media will be calling.
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> If you have text or photos or anything, I would really appreciate it.
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> Cc to Tracy and Bill as well.
>
> Thanks all.
>
> Sent from my iPad

--

Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

GOODBYE TO THE GLACIERS

The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. They are now rapidly shrinking due to human-caused climate change. Computer models indicate the glaciers will all be gone by the year 2020.

Glacier National Park was named for the sculpting actions of the Pleistocene glaciers that covered this landscape 12,000 to 130,000 years ago.

Park glaciers between 1850 and 2020

- 1850
- 1900
- 1950
- 1980
- 2000
- 2020 *(projected)*

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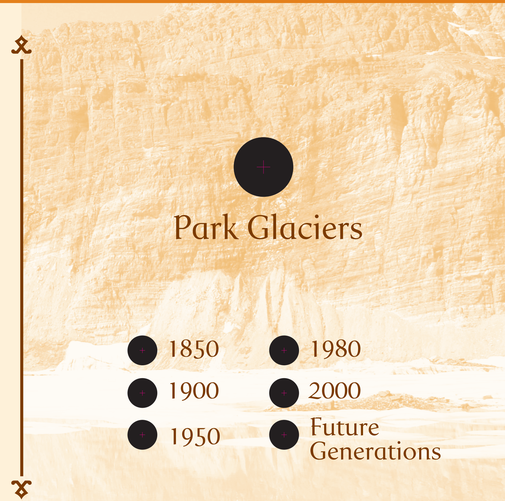
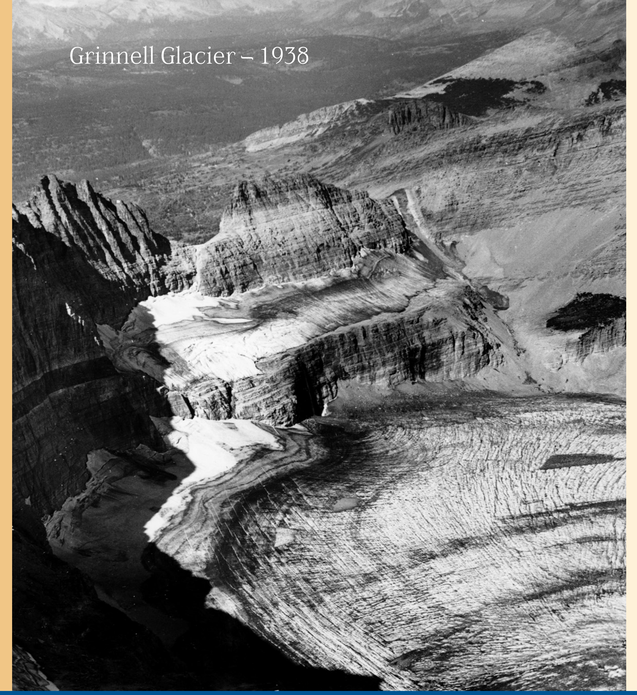
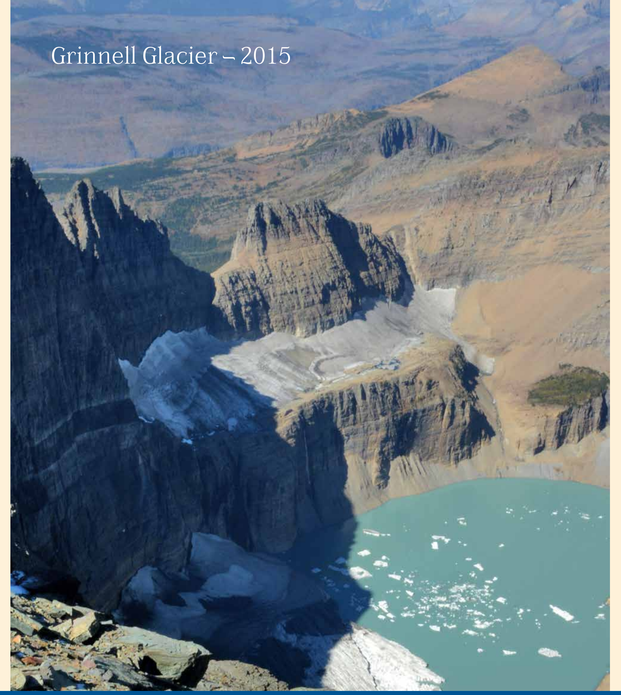
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum size and number around 1850, at the end of the Little Ice Age. Currently, they are rapidly shrinking due to human-accelerated climate change. When they will completely disappear, however, depends on how and when we act.



Glaciers are moving masses of ice. During the Pleistocene—12,000–130,000 years ago—the massive glaciers shaping this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

In 1850 there were about 150 glaciers in the park. In 2015, only 26 named glaciers remained in the park.

Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking. Grinnell Glacier, located high in the Many Glacier Valley, has lost 45% of its area in recent decades.

GLACIERS ON THE MOVE

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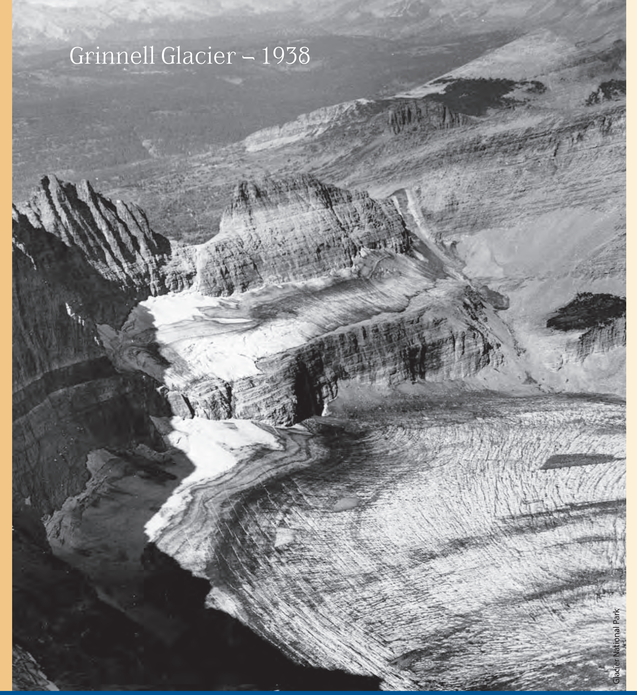

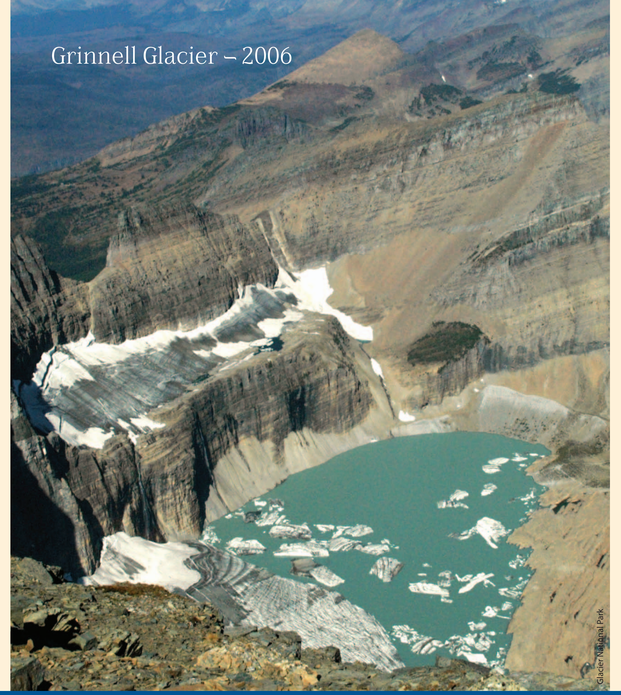

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Grinnell Glacier, located high in the Many Glacier valley, has significantly retreated in recent decades.

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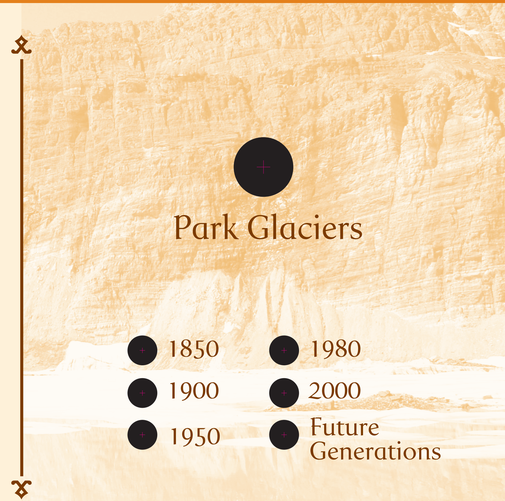

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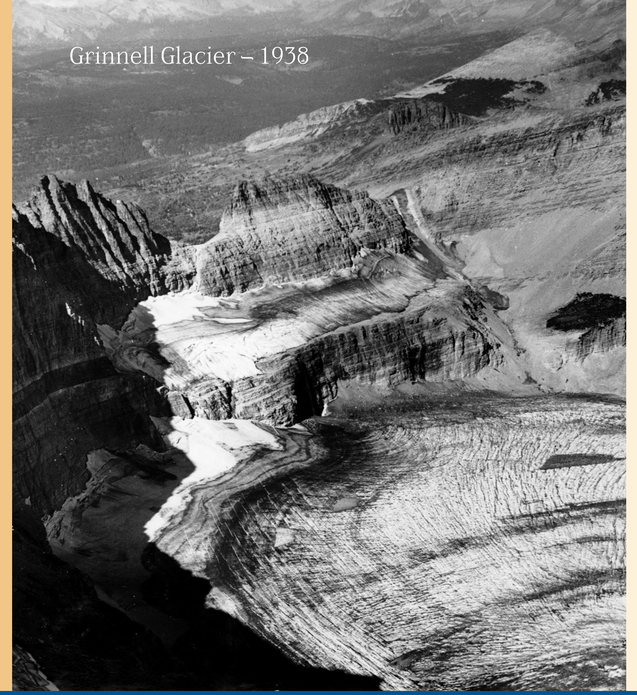

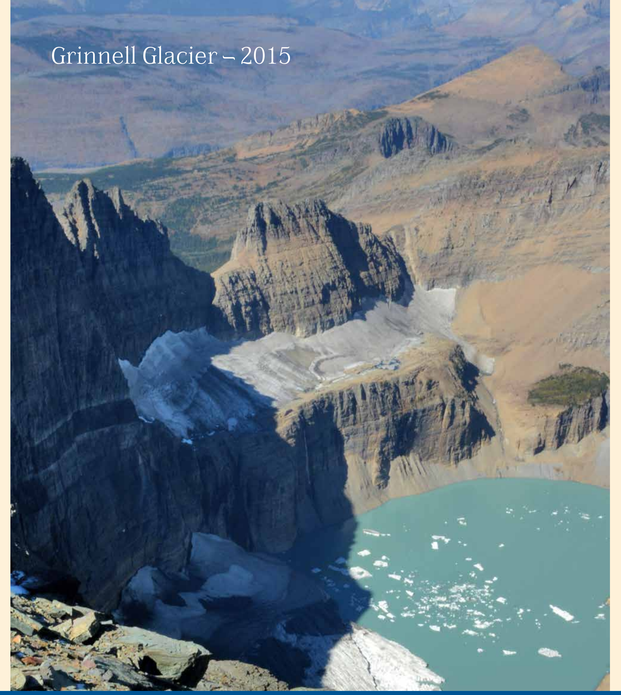

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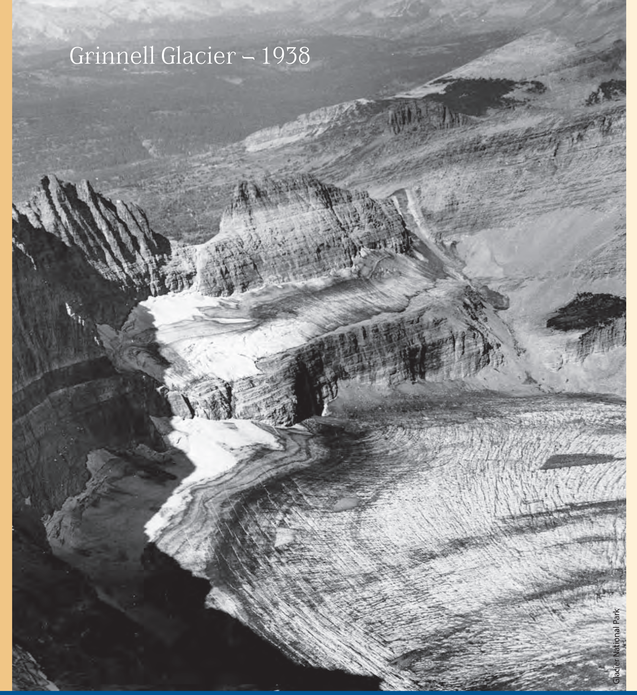

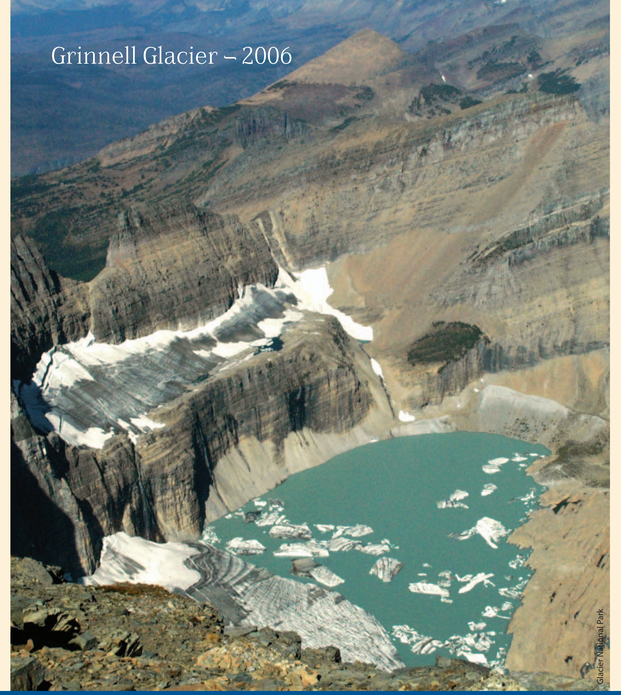

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GLACIERS ON THE MOVE

Conversation Contents

Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Sat Jun 08 2019 16:31:30 GMT-0600 (MDT)
To:	Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Bill,
Thank you so very much for the comprehensive information you provided in the other email you sent, with exhibit attachments. Note this email from Jeff and some of the additional information that he will also be looking for us to provide on Monday. In particular it is apparent that Jeff has an interest in seeing how these may associate with deferred maintenance and the maintenance backlog. You went above and beyond the call of duty today! Thank you so much!

---------- Forwarded message ---------
From: **Jeff Mow** <jeff_mow@nps.gov>
Date: Sat, Jun 8, 2019, 3:54 PM
Subject: Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage
To: Lauren Alley <lauren_alley@nps.gov>
Cc: <dan_fagre@usgs.gov>, <Melissa_Sladek@nps.gov>, <tara_carolin@nps.gov>, <tracy_ammerman@nps.gov>, <phil_wilson@nps.gov>

All

Debby and I touched base on this yesterday and we said we'd circle up on the process on Monday. A couple of things I'd like to know

1) how old are these exhibits
2) when did we put these into pmis for replacement funding
3) how many exhibits overall do we have in pmis for cyclic funding replacement
4) am I correct in assuming that the lion's share of exhibit panels that make reference to When the glaciers will disappear use the 2030 date. The 2020 date is an outlier.

To me there is a backstory that may have a connection to DM. We have so many trails, roads, restrooms, campgrounds, water systems, and wayside exhibits that are in line for replacement or rehabilitation and as we all know it can takes years for things to move up in the priority list.

I have no idea if these exhibits are in The system like the interpretive waysides are so this theme may not apply.

Sent from my iPhone

On Jun 8, 2019, at 3:12 PM, Lauren Alley <lauren_alley@nps.gov> wrote:

All -

I am circling back with you on what WASO and DOI have proposed below. From media outlets, it appears they're already using it (the stuff in gray text that the park didn't develop). The story has gone fairly viral in the last 24 hours.

Dan - do you want us to use this, or something else?

From park perspective I'm hoping to track down exhibit text so we can hopefully proactively address this.

My main objective is to identify exactly what NPS/USGS said about 2020 and publicly acknowledge that via website to clear up any confusion and for transparency. Certainly nobody wants to "quietly" do something or hide something. If anyone has any proposed text for this specific point, I'd welcome it.

Thanks to anyone who can provide input over the weekend. My guess is that by Monday at 8 am, we're going to get even more calls.

Sent from my iPad

Begin forwarded message:

> **From:** "Kupper, Kathy" <kathy_kupper@nps.gov>
> **Date:** June 7, 2019 at 3:24:56 PM MDT
> **To:** "Block, Molly" <molly_block@ios.doi.gov>
> **Cc:** April Slayton <april_slayton@nps.gov>, "Barnum, Jeremy" <jeremy_barnum@nps.gov>, Karen Armstrong <karmstrong@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Paul Laustsen <plaustsen@usgs.gov>, Ryan McClymont <rmcclymont@usgs.gov>, Catherine Puckett <cpuckett@usgs.gov>
> **Subject: Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage**
>
> Hi Molly,
>
> April and I are OK with the statement. We are looping in park staff and a couple of other SMEs for awareness and their input on the statement. Dan Fagre from USGS (dan_fagre@usgs.gov) is the SME that can also take calls if needed.
>
> Thank you,
> Kathy
>
> Kathy Kupper
> Public Affairs Specialist
> Office of Communications
> National Park Service
> (202)513-7263
> www.nps.gov
>
> The National Park Service cares for special places saved by the American people so that all may experience our heritage.

On Fri, Jun 7, 2019 at 5:00 PM Block, Molly <molly_block@ios.doi.gov> wrote:

> Adding the Park Service. Let's get a desk statement we can send around. Here's what I shared with the Daily Caller:
>
> Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.
>
> The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.
>
> USGS regularly publicizes their research efforts. The National Park Service does not typically issue press releases for new interpretive displays or park signage.
>
> The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.
>
> On Fri, Jun 7, 2019 at 4:53 PM Karen Armstrong <karmstrong@usgs.gov> wrote:
>
>> How would you like to handle?
>>
>> Sent from my iPhone
>>
>> Begin forwarded message:
>>
>>> **From:** Cheyenne MacDonald <Cheyenne.Macdonald@mailonline.com>
>>> **Date:** June 7, 2019 at 4:48:07 PM EDT
>>> **To:** "karmstrong@usgs.gov" <karmstrong@usgs.gov>
>>> **Subject: [EXTERNAL] Daily Mail Inquiry - National Park Signage**
>>>
>>> Hi Karen! My name is Cheyenne, I'm the Science & Tech Editor at Dailymail.com. I'm reaching out in regards to a report that's been going around today, was hoping to get some additional context and verify the claims being made.
>>>
>>> The report, linked here, https://dailycaller.com/2019/06/07/national-park-glacier-warnings/ , claims signs at Glacier National Park that warned glaciers will disappear by 2020 due to climate change have been 'quietly removed' after 'several winters of heavy snowfall threw off climate model projections.'

I would appreciate if you could clarify a few points:

-Have the signs really been changed? If so, when and why

-What do the latest models suggest about the state of glaciers in the park?

-Is there any weight to claims that glaciers have grown in recent years due to heavier snowfall?

Any additional information you can provide on the subject would be great.

Thanks so much.

Best,

Cheyenne

Cheyenne MacDonald

US Science & Technology Editor

Daily Mail Online | @_cheymac

51 Astor Place, 9th Floor, New York, NY 10003

<image001.png>

<image002.png>

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--
Molly Block
Press Secretary
U.S. Department of the Interior

Conversation Contents

Re: Exhibit text and/or photos ASAP?

Deborah Smith <debby_smith@nps.gov>

From:	Deborah Smith <debby_smith@nps.gov>
Sent:	Sat Jun 08 2019 16:03:03 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>, lee_rademaker@nps.gov
CC:	Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject:	Re: Exhibit text and/or photos ASAP?

Actually Bill (or Daniel for sure) should have all of this. I'm in town right now, but I can look when I get back and I think I also have the new panel in my email from when Daniel sent it to Lee and I to proof. I'm around this weekend, but Lee is back in Helena this weekend.

I'll be in touch...

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

-------- Original Message --------
From: Lauren Alley <lauren_alley@nps.gov>
Date: Sat, June 08, 2019 3:05 PM -0600
To: lee_rademaker@nps.gov, debby_smith@nps.gov
CC: Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject: Exhibit text and/or photos ASAP?

Hey Lee and Debby -

Are either of you working today or tomorrow?

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My guess is that by Monday morning, main stream media will be calling.

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Cc to Tracy and Bill as well.

Thanks all.

Sent from my iPad

Conversation Contents

academic sources I've been using to understand how long the glaciers will be active

Attachments:

/6. academic sources I've been using to understand how long the glaciers will be active/1.1 Brown_2010_GPC (1).pdf
/6. academic sources I've been using to understand how long the glaciers will be active/1.2 Bosson_et_al-2019-Earth's_Future.pdf
/6. academic sources I've been using to understand how long the glaciers will be active/1.3 Clarke_2015_NatureGeoscience.pdf
/6. academic sources I've been using to understand how long the glaciers will be active/1.4 Huss_2017_EarthsFuture.pdf
/6. academic sources I've been using to understand how long the glaciers will be active/1.5 Bosson_et_al_2019_EarthsFuture_Suppporting_Information.docx

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Sat Jun 08 2019 15:59:36 GMT-0600 (MDT)
To:	William Hayden <bill_hayden@nps.gov>
Subject:	academic sources I've been using to understand how long the glaciers will be active
Attachments:	Brown_2010_GPC (1).pdf Bosson_et_al-2019-Earth's_Future.pdf Clarke_2015_NatureGeoscience.pdf Huss_2017_EarthsFuture.pdf Bosson_et_al_2019_EarthsFuture_Suppporting_Information.docx

Bosson 2019 has charts showing predictions for glaciers around the world
Bosson 2019 Supporting Information has predictions for glaciers in Glacier National Park
Brown 2010 has predictions for Sperry Glacier
Clarke 2015 has regional glacier predictions
Huss 2017 has more regional glacier predictions

ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/228401197

Cirque glacier sensitivity to 21st century warming: Sperry Glacier, Rocky Mountains, USA

Article *in* Global and Planetary Change · November 2010

Impact Factor: 2.77 · DOI: 10.1016/j.gloplacha.2010.09.001

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Cirque glacier sensitivity to 21st century warming: Sperry Glacier, Rocky Mountains, USA

Joel Brown [a,b,*], Joel Harper [a], Neil Humphrey [c]

[a] Department of Geosciences, University of Montana, 32 Campus Dr., Missoula, MT 59812, USA
[b] Center for Geophysical Investigation of the Shallow Subsurface, Boise State University, 1910 University Dr., Boise, ID 83725, USA
[c] Geology and Geophysics Department 3006, University of Wyoming, Laramie, WY 82071, USA

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Article history:
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Keywords:
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cirque glacier
glacier modeling

ABSTRACT

The interpretation of climate change based on the behavior of small cirque glaciers is not always straightforward or unique. In this study of Sperry Glacier, Glacier National Park, Montana, we model future change of the glacier under 11 different warming scenarios. The scenarios vary from no warming from present conditions to warming at a linear rate of 10 °C/century. We assume constant precipitation and only consider change invoked by warming. Our cellular automata model is based on simple rules that account for mass balance gradient, aspect, avalanching, and the flow of ice to redistribute mass. We constrain the model with glaciological data including georadar-measured ice depth, field-measured surface mass balance, and field-mapped ice surface topography. Under the most probable temperature increase based on downscaled OA-GCM output for the IPCC A1B scenario, we conservatively estimate the glacier persisting through at least 2080. By comparing glacier volume responses to different warming scenarios we elucidate a relationship between the magnitude of temperature change and the sensitivity of the glacier to small variations in the temperature increase. We find that the greater the magnitude of the temperature increase, the less sensitive the glacier area and volume become to slight differences in the warming rate. If we generalize this relationship to the region, we expect that a small change in climate will produce varying responses for glaciers throughout the region, whereas the glacier response to a large change in climate will likely be very similar over the entire region.

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1. Introduction

Area and volume adjustments of mountain glaciers have important impacts on society and natural systems. Most notable are the contributions of mountain glaciers to sea level rise (e.g., Meier and Dyurgerov, 2002; Bahr et al., 2009), and the influence of mountain glaciers on water resources and geomorphic hazards (e.g., Moore et al., 2009; Leiva et al., 2007). Since mountain glaciers are considered sensitive indicators of climate, they are used to detect and monitor local climate change in regions not typically monitored by instrumentation (e.g., Haeberli et al., 2007). Further, observations of glacier change are independent from potential issues related to the location, instrumentation, and processing of weather station data. Consequently, the general global retreat of mountain glaciers (Dyurgerov and Meier, 2000) is commonly cited as corroborating evidence for 20th century climate warming of the instrumental temperature record. For example, Oerlemans (2005) used the length records of 169 glaciers located around the world to construct a quantitative record of 20th century warming, and found that the glacier record agreed remarkably well with the instrumental record.

With projected increases to the rate of warming in the 21st century (IPCC, 2007), a general acceleration of rates of glacier retreat appears likely. For many small mountain glaciers, projecting their recent rate of retreat forward implies they will disappear within the 21st century (e.g., Nesje et al., 2008). However, the small glaciers within a region do not always advance or retreat at the same rate as large ones (Granshaw and Fountain, 2006; Fountain et al., 2009) and past advances or retreats of a glacier may not indicate how that glacier will change in the future. As mountain glaciers become small, many begin to occupy little more than the area below their cirque headwall. Near the cirque, winter snow accumulation is often enhanced from wind drifting and avalanching from the steep cliffs above, while radiation shading reduces summer ablation (Kuhn, 1995). Consequently, cirque glaciers are sometimes considered products of topography and therefore inappropriate indicators of climate variability and change (Kuhn, 1995). In addition, climate change within a region is not typically spatially uniform (e.g., Shindell and Faluvegi, 2009). Therefore, similar glaciers in different basins within the same region may not experience identical changes in climate and thus may have slightly different volume and area changes.

* Corresponding author. Geosciences Department, The University of Montana, 32 Campus Drive #1296, Missoula, MT 59812-1296, USA. Tel.: +1 406 370 1775; fax: +1 406 243 4028.
E-mail address: jbrown@cgiss.boisestate.edu (J. Brown).

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doi:10.1016/j.gloplacha.2010.09.001

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Some small cirque glaciers may be more (or less) sensitive to climate change than other small cirque glaciers, making the interpretation of climate based on small glaciers difficult. In the Cascade Mountains of Washington State, U.S., larger glaciers lost less fractional area than smaller glaciers during last half of the 20th century (Granshaw and Fountain, 2006). Further north in a western Canadian mountain range, DeBeer and Sharp (2009) found that 75 of 86 small glaciers showed no observable size change during a similar time period. The lack of change implies that either this mountain region experienced no late 20th century warming, or that the small glaciers failed to respond to any warming. The authors suggest the lack of glacier change was due to the small size and sheltered locations of glaciers which allowed them to be roughly in balance with late 20th century climate conditions. In a study covering ~10^6 km^2 of western Canada between 1985 and 2005, Bolch et al. (2010) show highly variable reductions in area of glaciers less than 5 km^2, but many showing reductions of several tens of percent. Hence, projecting future change of small glaciers, or interpreting their ongoing changes, requires detailed understanding of the circumstances dictating their climate sensitivity.

Here we examine the climate sensitivity of a small cirque glacier (~0.8 km^2) in the northern Rocky Mountains, USA. Rather than analyze historical variations, we investigate the response of an existing glacier to a wide range of potential future warming scenarios. Our purpose is to use this glacier for which we have detailed field measurements to explore the processes dictating the climate sensitivity of small cirque glaciers. We find that under large-magnitude warming the glacier undergoes rapid area and volume reductions that are insensitive to minor variations to the warming rate. Under small-magnitude warming, however, slight differences in the warming rate yield large volume and area differences in the glacier.

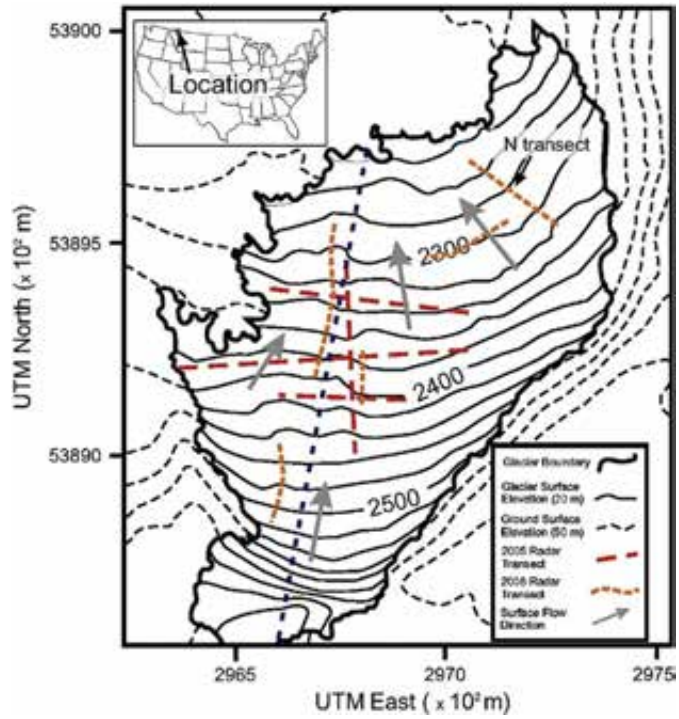

Fig. 1. Topographic map of Sperry Glacier surface derived from GPS measurements. Red dashed lines show location of 5 MHz radar transects collected in 2005, orange dashed curves show location of 5 MHz radar transects collected in 2008. Gray arrows indicate direction of ice flow. The blue dashed line trending roughly North-South is the location of the profiles in Fig. 6. The location of radar transect that is shown in Fig. 2 (N transect) is labeled.

2. Study glacier and glaciological setting

Sperry Glacier is a small cirque glacier located in Glacier National Park, Montana. The glacier is ~1 km wide, ~1 km long, has an average slope of ~10°, and sits beneath a cirque wall that extends upward 100–300 m (Fig. 1). Historic photographs reveal that since the start of the 20th century Sperry Glacier has lost approximately 78% of its area (Pederson et al., 2006) and has incurred a corresponding (but unquantified) reduction in volume. The climate conditions at Sperry Glacier during this period are undocumented, but during this time period global mean temperatures rose ~0.8 °C (Hansen et al., 2006) and some western Montana records experienced rises in extreme and seasonal average temperatures (Pederson et al., 2010). Historical trends of retreat of two other glaciers in Glacier National Park imply that projected 21st century warming could cause them to disappear in the next few decades if those trends were to continue (Hall and Fagre, 2003). However, we can make a zero-order estimate of Sperry Glacier's minimum longevity by applying the recent ablation rate at the terminus (−2 m/year) to the entire glacier, which we assume to average 35 m deep (this ablation rate and ice depth are justified below). This yields a time constant of ~18 years. Considering that this estimate assumes a very high ablation rate with no mass accumulation it is apparent that the glacier's lifetime will extend substantially beyond 18 years.

3. Methods

Future changes to mountain glaciers have been investigated with models of differing complexity and computational expense. For example, Paul et al. (2007) used a highly simplified approach that combines hypsographic analysis with an accumulation area ratio and neglects the redistribution of mass by ice flow. This approach requires minimal computational resources and therefore enables large regions (i.e., the Alps) and a wide variety of future scenarios to be explored (e.g., Paul et al., 2007). Schneeberger et al. (2003) used a much more complex approach by coupling an Atmosphere-Ocean General Circulation Model (OA-GCM), a glacier mass-balance model, and a glaciological flow model, which obviously required significant computational power as well as detailed input data for each modeled glacier.

Here we use an intermediate level of model complexity to investigate the response of Sperry Glacier to various warming scenarios. We model current and future glacier-climate conditions with a model constrained by field measurements of the glacier's surface mass balance and ice thickness. Our approach addresses 3-dimensional topography and incorporates vertically integrated ice flow dynamics, but our model is highly simplified and computationally inexpensive. The advantage of this approach is that it allows us to explore many different warming scenarios without neglecting mass transfer. A high degree of uncertainty surrounds future climate change and our aim is not to forecast the future of Sperry Glacier specifically. Rather, our goal is to investigate the range of responses of this small cirque glacier to different degrees of warming and to examine the glacier's sensitivity to different magnitude temperature variations.

3.1. Model construct and input

To simulate the mass balance and motion of Sperry Glacier we use a cellular automata (CA) model adapted from Harper and Humphrey (2003). The CA model uses a set of rules to accumulate, ablate, and move units of water equivalent over topographic cells of a landscape. The CA model requires as inputs Digital Elevation Models (DEMs) of the glacier surface and bed, and the annual net mass balance (B_n) defined according to elevation, slope, and aspect. The origin of the mass balance inputs are described in more detail in Section 3.1.2 (below). An annual time step in the modeling sequence consists of

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adding the water equivalent of the B_n (positive or negative) to each cell of the DEM. Mass is then transferred between cells via "avalanching" and "ice flow" (described below in Section 3.1.3). Iterations of mass transfer occur until no cells satisfy flow or avalanche criteria. In other words, the model converges each year when the glacier geometry fully adjusts by mass transfer to the mass gains and losses for that year. After the CA model converges, the surface DEM is updated to account for the small changes in glacier thickness and areal extent. This updated DEM is then used as the initial condition for the next annual time step and the process is repeated.

The model converts surface and bed DEMs from orthogonal to hexagonal cells. This allows for six degrees of freedom for particle motion between adjacent cells. Both avalanching and ice flow criteria are dependent on surface slope; thus, each cell has six slope values with associated directions. We compute the slope from the difference in elevation between cells divided by the distance between the centers of the cells. After the surface DEM is updated in surface slopes are recalculated for the subsequent time step.

3.1.1. Ice surface and bed topography

We used field measurements to determine the elevation of the current glacier surface, the current glacier volume, and the elevation of the bed surface. We measured the current elevation of the glacier surface in 2008 with GPS data collected with Trimble GeoXH and Trimble R7 receivers. The error of the GPS measurements is less than 1 m in the x and y directions and ~1 m in the vertical direction. We used a Kriging algorithm to generate a 10-m ice surface DEM and combined it with a 10-m terrain DEM (available from the U.S. Geological Survey) to include adjacent bedrock topography.

To measure the glacier thickness we used a 10-MHz Narod Geophysics type georadar transmitter and oscilloscope receiver. Our data were collected on 5-m spacing along transects and were georeferenced using a hand-held GPS receiver (accurate to 1–3 m). In total we collected nine transects, four in 2005 and five in 2008 (Fig. 1). We identified the two-way travel time (TWT) of the first reflection of the bed for each trace and converted the TWT to depth assuming a constant radar velocity of 0.168 m/ns (Fig. 2). Based on this propagation velocity, the ¼ wavelength resolution (Annan, 2005, p. 380) of the radar is ~4.2 m. We assume that all reflections come from directly below the acquisition point and we used a Kriging gridding algorithm to interpolate the ice depths over the area covered by Sperry Glacier using the edge of the ice surface as zero depth points. The final bed surface topography was generated by subtracting the interpolated ice thickness from the surface DEM. The surface and bed DEMs serve as initial condition inputs for our model runs.

3.1.2. Mass balance

Our model requires a prescribed function for mass balance versus elevation. Our function is based on 2 years of field measured surface mass balance and other meteorological and glaciological measurements in the basin (Reardon and Harper, unpublished USGS report). The function consists of two different linear gradients, one for above the ELA and one for below the ELA (Fig. 3). We generated the lower mass balance gradient by linearly fitting field observations of net annual mass balance vs. elevation. The data used to determine the lower elevation mass balance gradient were primarily acquired in the ablation area of the glacier and were spatially averaged across the width of the glacier. We found the mass balance gradient in the lower elevations to be $+7.5\times10^{-3}$ m of water equivalent per 1 m rise in elevation (0.0075 m m^{-1}). A net ice loss of ~2 m water equivalent occurred at the terminus (~2300 m elevation contour) all 4 years that we measured mass balance. Based on the mass balance gradient upward from the terminus, the ELA should be located at ~2570 m. However, field measurements and late summer photographs (Fig. 4) indicate that the ELA is actually lower, ranging between about ~2420–2550 m (depending on aspect). We attribute this lowered ELA and calculated climatic ELA to avalanching, wind drifting, and lower melt rates due to shading on the upper reaches of the glacier; which are represented by a higher mass balance gradient in the accumulation zone. After avalanching and flow are accounted for, the modeled ELA matches recent observations of the position of the observed ELA.

Sperry Glacier occupies a north-facing basin, but the surrounding topography with more southerly aspect and similar elevation range does not support perennial ice. To account for aspect-dependent mass balance we defined six aspect directions based on direction of the steepest slope for each cell and allowed positive mass balance only on the three north-most facing aspects. This matches present and historical observations, with ice existing at Sperry Glacier but not on adjacent southerly aspects.

3.1.3. Mass transfer

Ice movement is modeled by assuming that flow will occur when basal shear stress (τ_b) exceeds a critical value of 10^5 Pa (Nye, 1951). Hence, the model utilizes the common simplification that ice deforms as a pure plastic (Paterson, 1994; Hooke, 1998) and both ice deformation and basal sliding act to keep τ_b just below a yield stress. When τ_b exceeds 10^5 Pa in a cell, enough mass is transferred out of that cell to bring τ_b to just below the yield stress. Basal shear stress is calculated as:

$$\tau_b = \rho_i g h \sin(\theta), \tag{1}$$

where ρ_i is the density of ice (900 kg m^{-3}), g is the acceleration due to gravity (~9.8 m/s), h is depth of ice, and θ is defined as $\tan^{-1}(\Delta Z/\Delta d)$

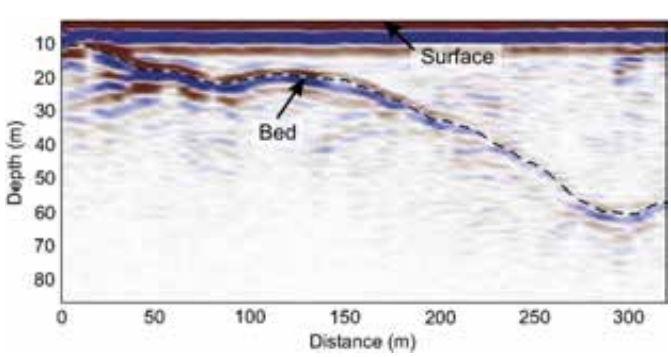

Fig. 2. Radar transect from Sperry Glacier. The bed reflection is clear across the profile. Depths are calculated with an assumed constant velocity of 1.68x10^8 m/s. The location of the transect (N transect) is shown on Fig. 1.

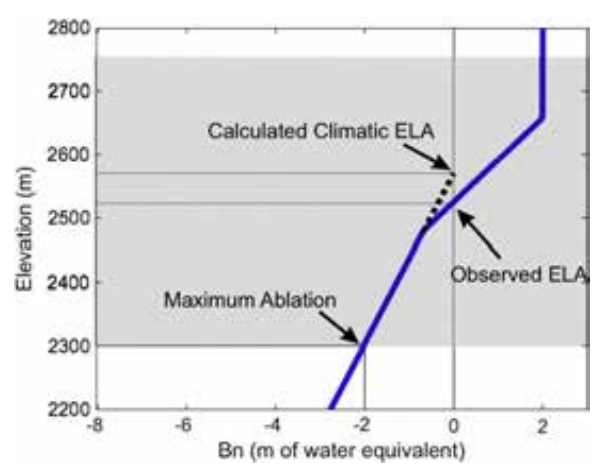

Fig. 3. Mass balance curve used as input for modeling. Elevation range spanned by Sperry Glacier is delineated by the gray shaded area. Locations of the calculated climatic ELA, observed ELA, and maximum ablation elevation are marked.

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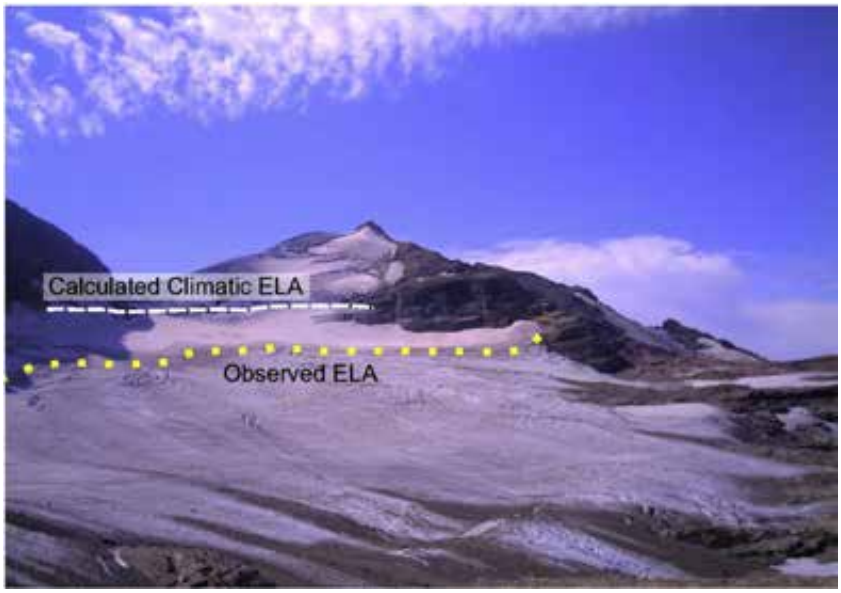

Fig. 4. Photograph of Sperry Glacier taken on 8-31-2007 as part of a time-lapse photo study. The approximate location of the calculated climatic ELA is marked with a white dashed curve; the observed ELA is marked with a yellow dotted curve. The location of the observed ELA in 2007 was higher than in all other observed years. The region of the glacier that is in view in this photograph is approximately 1 km.

where ΔZ is the difference between adjacent cell surface elevations and Δd is the distance between the center point of two adjacent cells. After τ_b stabilizes below 10^5 Pa on all cells of the glacier, another year of annual mass balance (negative or positive values) is applied to the surface, slopes and basal shear stresses are recalculated, and mass is again moved by avalanching and ice flow.

The upper portion of Sperry Glacier receives enhanced accumulation due to avalanching from the adjacent cirque wall. This is evident from large avalanche debris piles in this area witnessed every spring. To simulate this avalanching, cells with slopes greater than 30° and ice thickness less than 10 m pass their mass accumulation downslope with each annual time step. The 10 m ice thickness cutoff is used allow potential ice falls to form on steep slopes.

3.2. Warming scenarios

We modeled two different climate warming scenarios: (1) no temperature change. The initial mass balance curve (which produces an overall negative mass balance of the glacier) is constant during the 21st century; and (2) linear warming rates. The temperature increases each year by a constant amount so that a target temperature is achieved 100 years after 2008. This scenario was run for 1–10 °C/century warming rates at 1 °C intervals thereby producing 10 sub-scenarios. The IPCC Fourth Assessment Report projections show global surface temperature likely increasing 1.1–5.4 °C by the year 2100 for future emission scenarios A1B, A2, and B1 with the best estimate for temperature increase of 2.8 °C, 3.4 °C, and 1.8 °C respectively for the three scenarios. Locally, an analysis of downscaled OA-GCM output (Coupled Model Intercomparison Project phase 3) for high elevations in northwest Montana found that under scenario A1B the probability distribution function peaks at 0.28 for an end of century mean temperature increase of 3 °C (Gillan et al., 2010). The span of the 0.20 probabilities for end of century temperature increases is 0.5 °C to 6.4 °C warming, and the 0.10 probabilities have a range of a −0.5 °C cooling to a 7.1 °C warming. Our suite of scenarios therefore spans a wide range of projections and includes the tails of the probability distribution for most projections. Specifically, the A1B projection of 3 °C by 2100 is bracketed by our 3 °C/century and 4 °C/century warming rate scenarios which reach +2.76 °C and +3.68 °C in the year 2100, respectively.

Oerlemans (2001) shows that ELA change can be related to change in the mean free-air temperature by:

$$\Delta \mathrm{ELA} = \frac{1}{\gamma}\Delta T_{\mathrm{fa}}, \tag{2}$$

where γ is the local temperature lapse rate. We use the theoretical average lapse rate value of $\gamma = 0.007$ K/m (Oerlemans, 2001) because reported local lapse rates (Finklin, 1986) are variable and overlap with the theoretical. Using this average value of 0.007 K/m implies that for every Kelvin increase in T_{fa} the ELA rises 143 m. We use this relationship to estimate how various changes in T_{fa} will affect the future volume and area of Sperry Glacier. We note that 21st century climate change in northwest Montana may also involve change in precipitation. Climate models project precipitation change of roughly ±5% for northwest Montana, but projections have low confidence and high variance. We therefore do not address precipitation changes in this paper and our results reflect temperature change only in the absence of substantial precipitation change.

Each modeled climate scenario uses the 2008 glacier geometry, ice volume, and mass balance distribution (described in Section 3.1.2) as initial conditions. All model scenarios were run for a 100-year time period, allowing 2 years for model ramp-up time. We output the geometry, volume, and area of the modeled glacier after each year.

4. Results

The 'no change' scenario offers perspective on future changes if the recent average annual mass balance distribution, which has been negative, were to continue indefinitely. Our radar and GPS measurements show the current ice volume to be ~2.59×10^7 m^3 and the maximum depth to be ~80 m. With no increase in T_{fa} the modeled glacier shows a decrease in volume of about 26% and a decrease in area of 19% by ~2030, implying that the glacier is not in equilibrium with current climate. The glacier then remains stable to the end of the century (Fig. 5A and B). A cross-sectional view (Fig. 6A) shows that under these conditions Sperry Glacier retreats ~200 m by 2030. Although the lower elevation portions of the glacier thins and retreats, the upper elevations (above ~2525 m) remain relatively unchanged from the 2008 glacier. The majority of the ice area lost by 2100 is from

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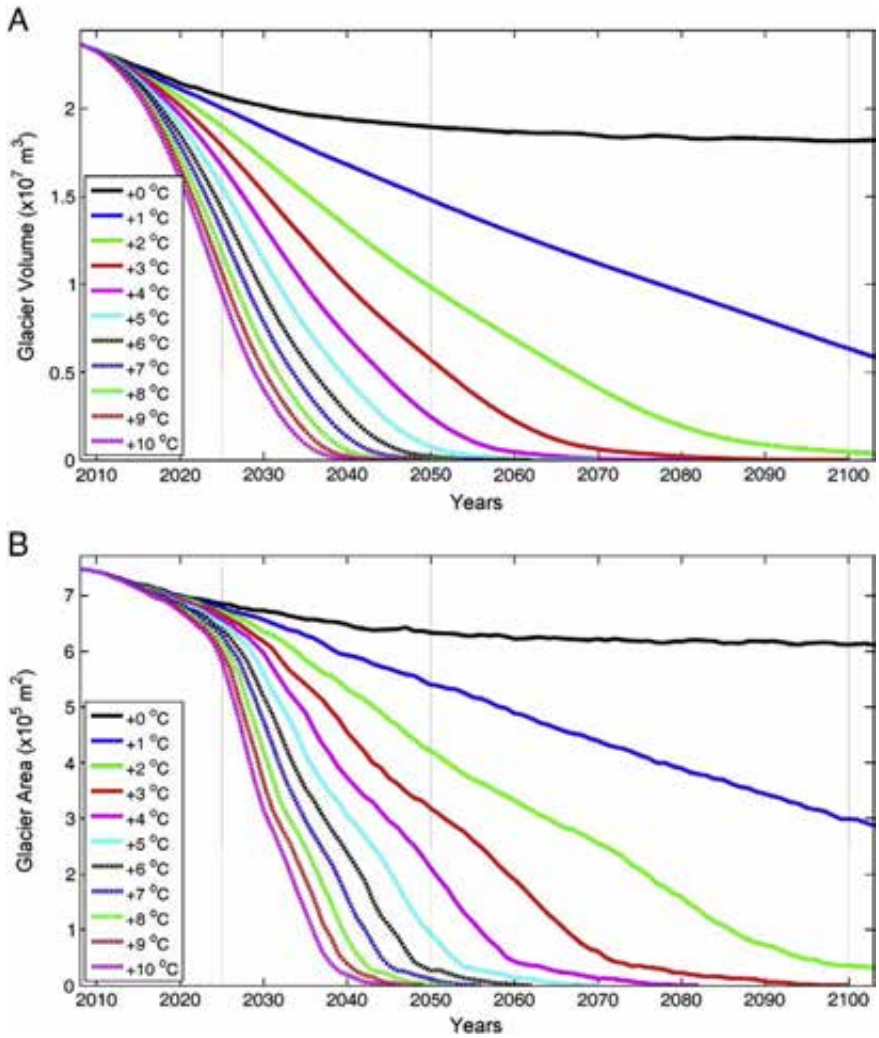

Fig. 5. (A) Total volume vs. time and (B) total area vs. time curves for all model scenarios used in this study. Legend numbers are total degree per century temperature increases. Since modeled temperature increase is simulated by ELA increase (text Eq. (1)) the baseline 'current' temperature is 0.

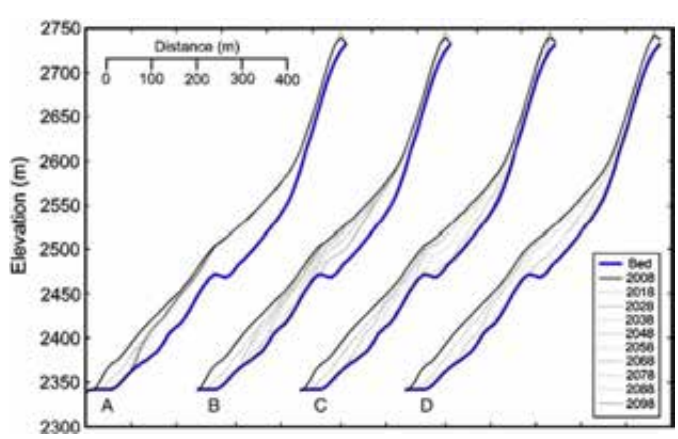

Fig. 6. Elevation profiles for four different modeled scenarios: (A) current B_n, (B) linear increase in temperature of 1 °C per century, (C) linear increase in temperature of 2 °C per century, and (D) linear increase in temperature of 3 °C per century. Each plot shows the bed elevation profile (blue line), the initial (2008) ice surface elevation profile (black line), the ice surface elevation profile in 2098 (red line), and the ice surface elevation profile for every 10 years between 2008 and 2098 (dotted lines). The location of the elevation profile on Sperry Glacier is marked on Fig. 1 (blue dotted line). The profiles are vertically exaggerated by 2.

the lowest elevations where influence from avalanching is minimal or non-existent (Fig. 7B).

With a 1 °C/century warming, the glacier persists in 2100 (Fig. 5A and B) but the area and volume decrease from current values by ~60% and ~75%, respectively. The rate of volume and area reductions are close to linear over the entire modeled time period for the +1 °C/century scenario. Notably, the glacier's rate of area and volume loss tracks the linearly increasing temperature for the entire time span modeled in this scenario, whereas the rate of area and volume loss under warmer scenarios takes 5–10 year to become linear. With a warming of 2 °C/century, the area decreases 95% and the volume is reduced 97% by 2100. Despite dramatic reductions in glacier area (Fig. 6D), the remaining ice is up to 30 m deep. With a warming rate of 3 °C/century the area and volume both decrease by 99.9% by 2100 effectively eliminating the glacier. Hence, the 1 °C/century and 2 °C/century warming rate scenarios do not cause the glacier to disappear, while the 3 °C/century warming rate scenario has it disappearing at about 2100. Since the downscaled AO-GCM prediction of the A1B scenario of 3 °C temperature increase by 2100 is bracketed by our 3 °C/century and 4 °C/century warming rate scenarios our model results conservatively estimate the glacier existing past the year 2080 under the A1B scenario. All warming rate scenarios above 3 °C/century result in the glacier disappearing prior to 2100. Under these scenarios, volume quickly decreases, while area changes take ~10 years to decrease substantially (Fig. 5). As the glacier nears zero

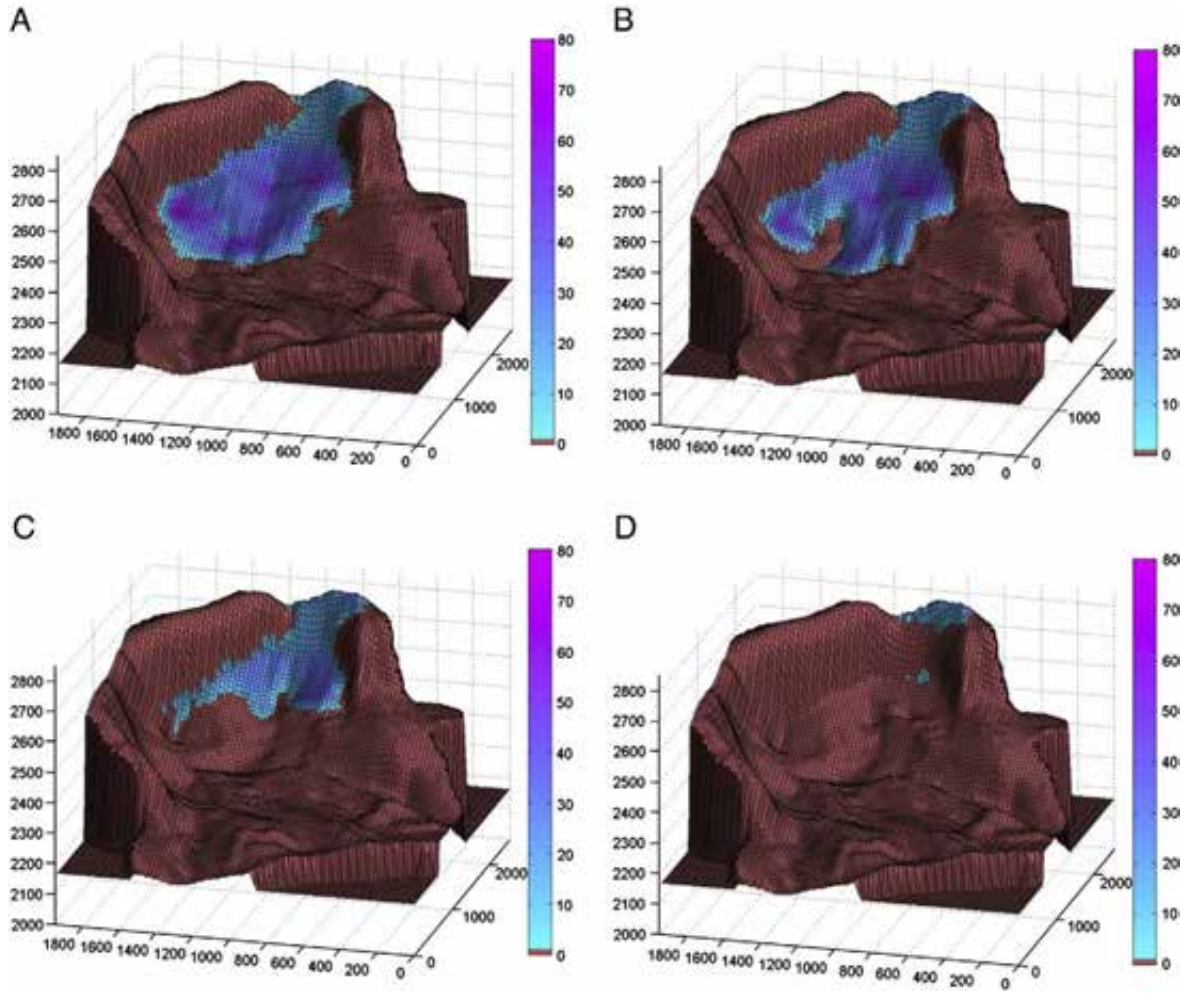

Fig. 7. Model DEM outputs of Sperry Glacier extent and depth including: (A) the interpolated glacier that is the initial condition for all model runs, (B) modeled glacier in the year 2100 under the current B_n scenario, (C) modeled glacier in the year 2100 under the 1 °C per century increase scenario, and (D) modeled glacier in the year 2100 under the 2 °C per century increase scenario. Brown is the current glacier bed (where ablation has occurred) and the surrounding topography, blue to purple is ice depth from 0 m to 80 m, respectively.

volume and area, rates of change slow again, as the only remaining ice occupies the highest, most sheltered part of the cirque wall. Our model shows that Sperry Glacier disappears by 2050 under a warming rate of 9 °C/century or greater (Table 1).

5. Discussion: sensitivity to warming rate

To quantitatively explore the sensitivity of Sperry Glacier to different warming scenarios we computed the ice volume difference between consecutive warming scenarios (i.e., +1 °C/century versus +2 °C/century) over time. At any time t, the volume difference between two consecutive warming scenarios ($\Lambda(t)$), is calculated as:

$$\Lambda(t)|_i = V(t)|_{T=i} - V(t)|_{T=i+1}, \quad (3)$$

where $V(t)|_{T=i}$ is the volume of Sperry Glacier with a warming rate of i °C/century above present temperature (note that i represents temperature rise at a rate of i/century so actual temperatures at any time $t<100$ will be less than i). Hence, $\Lambda(t)$ depicts how records of ice volume for warming scenarios which differ by 1 °C/century diverge

Table 1
Model calculated volume and area of the 11 scenarios included in this study. Each value is given for the years 2025, 2050, and 2100. All model runs assume a starting year of 2008.

Scenario	ΔT_{fa} (°C)	2025 Volume ($\times 10^7$ m^3)	2025 Area ($\times 10^5$ m^2)	2050 Volume ($\times 10^7$ m^3)	2050 Area ($\times 10^5$ m^2)	2100 Volume ($\times 10^7$ m^3)	2100 Area ($\times 10^5$ m^2)
Current B_n	0	2.0714	6.854	1.8954	6.335	1.8166	6.121
	1	2.0009	6.789	1.4799	5.399	0.6352	2.992
	2	1.8961	6.718	0.9832	4.207	0.0474	0.361
	3	1.7863	6.652	0.5700	3.178	0.0000	0.006
	4	1.6718	6.559	0.2453	2.106	0.0000	0.000
Linear rise over 100 years	5	1.5528	6.493	0.0754	0.930	0.0000	0.000
	6	1.4254	6.395	0.0224	0.274	0.0000	0.000
	7	1.3012	6.285	0.0051	0.1203	0.0000	0.000
	8	1.1786	6.160	0.0007	0.0219	0.0000	0.000
	9	1.0615	5.979	0.0000	0.000	0.0000	0.000
	10	0.3997	3.129	0.0000	0.000	0.0000	0.000

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from each other over time. A peak Λ value (max Λ), representing the biggest difference in volume between each 1 °C/century different warming rate, is reached 20 to 100 years in the future (Fig. 8A). The Λ values approach zero as scenario differences either reflect similar glaciers consisting of ice in only the highest elevations of the cirque, or total ablation of the glacier. We did analogous calculations with glacier area.

As expected, larger magnitude increases in warming rate result in larger and earlier reductions in glacier volume and area than do smaller magnitude warming rates. However, our analysis reveals the glacier has variable sensitivity to 1 °C/century differences in warming rate which dependents on the total magnitude of the warming rate, values of max Λ decay exponentially as the total magnitude of the warming rate increases (Fig. 8B and C). For example, max Λ_{volume} at $T=1$–2 is ~5.8 times greater than the max Λ_{volume} at $T=8$–9 and ~2.75 times greater than max Λ_{volume} at $T=4$–8. In other words, scenarios differing by 1 °C/century under low-magnitude warming produce very different ice volumes, but scenarios differing by 1 °C/century under high-magnitude warming result in a similar ice volume at any given time. The decay of max Λ is proportional to the inverse of the total magnitude of the temperature increase. Empirically, we find that:

$$\max \Lambda_{\text{volume}} \big|_{(T_i - T_0)} \propto \frac{1}{(T_i - T_0)^{\beta}}, \tag{4}$$

where, T_0 is the initial (pre-retreat) free air temperature, T_i is the free-air temperature i degrees above T_0, and β is an empirically derived constant that likely represents glacier geometry (i.e., ice depth and hypsometry) and mass balance gradient; for Sperry Glacier $\beta \approx 1.22$ (Fig. 8B, dashed line). The β value is therefore simply a scaling factor used to fit the curvature of the decay function.

Although a decay of max Λ with increasing T stems from the fact that a 1° increase in temperature is a smaller percentage increase of higher temperatures, the max Λ curve (Fig. 8) requires a scaling factor (β) for direct proportionality to $\frac{1}{(T_i - T_0)}$. Two competing processes dictate the growth of Λ over time and therefore the value of max Λ. First, the temperature difference between the two scenarios causes the melt rate of the higher temperature scenario to increase faster than the melt rate of the lower temperature scenario, thus causing Λ to increase over time. The growth rate is not linear, however, because the area of the glacier diminishes over time and there becomes less and less area for melt-rate differences to act on. Second, high elevation accumulation and the resultant mass transfer vary greatly over time between small warming rate scenarios. For example, an area of net accumulation and down-valley ice flow will persist for 73 years longer for a +1 °C/century warming rate than for a +2 °C/century warming rate, and the +2 °C/century warming rate scenario maintains an accumulation area for 25 years longer than a +3 °C/century warming rate scenario. For larger warming rates, however, accumulation and mass transfer processes do not vary significantly between scenarios because the ELA rises above the basin in a short time window (16 years between +6 °C/century and +10 °C/century warming rate scenarios). Thus, since there is very little variation in total accumulation under high-magnitude warming scenarios, these scenarios quickly converge to a similar condition where a nearly stagnate block of ice melts away. In contrast, because there is a large difference in total accumulation between different low magnitude warming scenarios, these scenarios have greater divergence of glacier area and volume adjustments over time.

Because future climate warming will likely have some degree of spatial variability (Shindell and Faluvegi, 2009), the glacier response throughout Glacier National Park could reflect this variability, depending upon the magnitude of warming. If warming is severe we could see little to no regional variability of glacier response with all

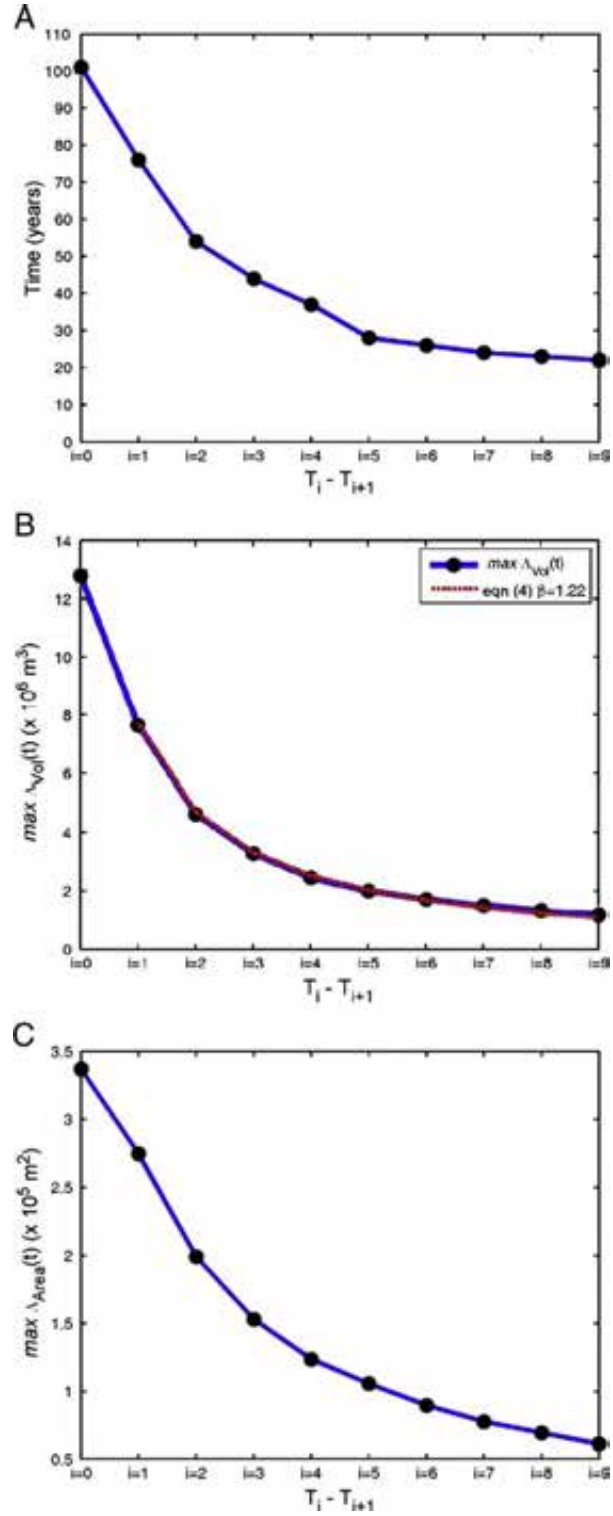

Fig. 8. Maximum value of the difference in ice volume (B) and area (C) between modeled scenarios differing by 1 °C and the time that the maximum volume difference occurs (A). The values of i represent the magnitude of the lower of the two temperature change scenarios being compared. For example, $i=1$ is the difference between the volume of the 1 °C per century linear temperature increase minus the volume of the 2 °C per century linear temperature increase at time t. Note that the $i=0$ point is maximum volume difference between a constant temperature model and a linearly increasing model, all other max Λ points show the relationship between 2 increasing temperature scenarios. Values on the x-axis are denoted by the i values (described in the text and in caption of Fig. 8). The red dotted line in B is the empirical fit to the max Λ_{volume} values (Eq. (4) in the text). Notice that the fit does not relate to the $i=0$ point because Λ is still increasing at 100 years thus the max Λ value is not representative of the value of the models were run for a much longer period.

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glaciers undergoing similar reductions in area and volume. However, if warming is slight, then the minor temperature variations between basins could lead to large regional variations in glacier area and volume changes. For Sperry Glacier, the threshold between the two modes of behavior is a warming rate on the order of 4–5 °C/century.

6. Conclusions

Unless the ELA rises above the highest elevation in the Sperry Glacier basin (~2800 m), there will be net annual accumulation at high elevations and the glacier will never totally disappear. Based on Eq. (2), a 2 °C increase in temperature is required to move the ELA to 2856 m elevation. The most probable projection based on downscaled OA-GCM output using the IPCC (2007) A1B scenario is ~3 °C warming in Northwest Montana by 2100. Our modeling work suggests that under these conditions the glacier will persist through at least 2080. Even for an extreme warming trajectory of 10 °C/century, the modeled glacier exists for another four decades. These results demonstrate the shortcomings of future projections of glacier change based on extrapolation of historical retreat rates.

Under scenarios of a warming climate, larger summer heat input causes greater ablation rates of cirque glaciers. If this greater ablation rate is not balanced by increased accumulation and mass transfer, cirque glaciers will lose mass. Global mean temperature rise has not been spatially homogenous nor is it expected to be in the future, particularly in mountain regions. Our modeling has shown that area and volume changes of Sperry Glacier are more sensitive to minor variations in temperature under low magnitude warming than high-magnitude warming. This has relevance for interpreting ongoing change and anticipating future change to small glaciers in a spatially heterogeneously warming climate.

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Earth's Future

RESEARCH ARTICLE
10.1029/2018EF001139

Key Points:
- First inventory and study of the 19,000 glaciers located in natural World Heritage sites is presented
- In response to anthropogenic warming, these glaciers are expected to lose 33% to 60% of their volume by 2100
- The conservation of World Heritage glaciers is paramount in a changing climate because of their key role in planetary ecosystems

Supporting Information:
- Supporting Information S1
- Table S1

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Disappearing World Heritage Glaciers as a Keystone of Nature Conservation in a Changing Climate

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Abstract Since 1972, the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Convention aims to identify and protect sites of Outstanding Universal Value for future generations. However, growing impacts of climate change are of the utmost concern for the integrity of many sites. Here, we inventory the glaciers present in natural World Heritage sites for the first time. We found 19,000 glaciers in 46 sites located all over the world. We analyze their recent evolution, current state, and project their mass change over the 21st century. Our results are based on a comprehensive review of the literature as well as a state-of-the-art glaciological model for computing glacier responses up to 2100. Illustrating the strong influence of CO_2 emission scenarios and human actions on future ice loss magnitude, we project the wastage of 33% to 60% of the 2017 cumulative ice volume of 12,000 km^3 of World Heritage glaciers by 2100. Furthermore, we expect complete glacier extinction in 8 to 21 of the investigated World Heritage sites until the end of the century, depending on the climate scenario. We suggest that World Heritage glaciers should be considered as analogs to endangered *umbrella*, *keystone*, and *flagship species*, whose conservation would secure wider environmental and social benefits at global scale.

Plain Language Summary The World Heritage convention aims at protecting the Earth's outmost assets and commits humanity to transmit them to future generations. However, many World Heritage sites are affected by anthropogenic climate change. Here, we present the first study on the glaciers located within the natural World Heritage sites. We inventoried 19,000 World Heritage glaciers and projected their mass changes over the 21st century. The results emphasize that major glacier decline will occur in these iconic sites in future decades. Nevertheless, ice loss magnitude will vary by a factor of 2 according to CO_2 emission scenarios and thus human activities. This study points out how the conservation of World Heritage glaciers could serve as a leverage and a target to tackle the unprecedented issue of climate change. Glaciers are more than disappearing passive climatic indicators. They are key components of planetary ecosystems that influence global climate and sea level, as well as water fluxes, human activities, or biodiversity at the regional scale. The conservation of these iconic endangered features could thus mobilize global-scale conservation and climate mitigation benefits. In this context, we show how drastic reduction of emissions will rapidly curb melt rates and safeguard a large glacier volume on the long term.

1. Introduction

The Convention Concerning the Protection of the World Cultural and Natural Heritage was conceived to protect the planet's most significant and irreplaceable places from loss or damage (United Nations Educational, Scientific and Cultural Organization, 1972). It constituted a major advance in conservation strategies by linking together, above any spatial and temporal boundaries, the preservation of natural and cultural heritage. Today, 247 natural World Heritage sites are listed for their Outstanding Universal Value (OUV)—in terms of natural beauty or importance for geological and biological diversity and processes—committing states and the international community to make the utmost effort to conserve and transmit them to future generations. Although the 1972 World Heritage Convention did not identify anthropogenic climate change (Intergovernmental Panel on Climate Change, 2013, 2018) among the major issues, it now represents one of the most serious threats to natural sites and is the main source of future threat (Osipova et al., 2017). Recent studies have shown how direct or cascading effects of climate change lead to negative impacts on inscribed sites in various regions (Allan et al., 2017; Hughes et al., 2017; Reimann et al., 2018; Scheffer et al., 2015). Major changes are also documented in polar and mountainous environments, where

ongoing warming is amplified (MRI Working Group, 2015). The fate of glaciers appears especially troubling as their global decline is both observed and predicted (Intergovernmental Panel on Climate Change, 2013; Marzeion et al., 2018; Zemp et al., 2015). Although studies exist on some glaciers located in World Heritage sites, their particular conservation status—that is, their recognition as outstanding natural assets or components of ecosystems that have to be protected for future generations—is almost never considered, and no comprehensive assessment of their state has been carried out. This paper addresses this gap by comparing natural World Heritage sites and the globally complete Randolph Glacier Inventory (RGI; Pfeffer et al., 2014). This first identification of World Heritage glaciers allowed us to review the literature on their recent evolution and to explore the potential mass change during 21st century by using an updated version of the Global Glacier Evolution Model (Huss & Hock, 2015), a sophisticated approach to compute the individual response of glaciers.

2. Data and Methods

2.1. Data

The boundaries of the 247 natural World Heritage sites originate from the World Database on Protected Areas. Following the adoption of the World Heritage Convention in 1972, cultural and natural sites of OUV have been inscribed on the World Heritage list since 1978 and, with the exception of Antarctica, are currently present across the world.

Glaciers are dynamical ice masses formed by snow compaction. Outlines of all glaciers worldwide are provided by the globally complete RGI version 6.0 (RGI Consortium, 2017). The acquisition dates of the glacier outlines range from 1943 to 2013 but are typically from the first decade of the 21st century (Table S1 in the supporting information). We used global digital elevation models from various sources (Howat et al., 2014; Jarvis et al., 2008; Morin et al., 2016; Tachikawa et al., 2011) to extract and aggregate into 10-m elevation bands the topography of each glacier. Ice thickness distribution at the inventory date was calculated for each glacier by a numerical method for inverting bedrock elevation from surface topography relying on the principles of ice flow dynamics (Huss & Farinotti, 2012). In order to run the glacier evolution model at the global scale, we used monthly near-surface air temperature and precipitation data from the ERA-Interim Reanalysis (Dee et al., 2011) for the period 1980–2016. Results of monthly 2-m air temperature and total precipitation of the Fifth Phase of the Coupled Model Intercomparison Project (Taylor et al., 2012) for 2017–2100 were used for the future and were downscaled to all glaciers individually (Huss & Hock, 2015). We use projections from 14 global circulation models forced by three emission scenarios (Representative Concentration Pathways, RCP: Meinshausen et al., 2011; RCP 2.6, drastic reduction of greenhouse gas emissions; RCP4.5, intermediate scenario; and RCP8.5, high emissions).

2.2. Glacier Inventory in Natural World Heritage Sites

A World Heritage glacier inventory was established by intersecting the outlines of all natural World Heritage sites with those of the >200,000 glaciers of the RGIv6.0 (e.g., Figure S1). Most of the inventoried glaciers (94%) have their whole area encompassed within the World Heritage sites, whereas other glaciers have only a part of their area within the latter. As the Greenland ice sheet outlines are not included in the RGI, we used satellite-derived data (09.2016 MeASUREs Greenland Mosaics from Haran et al., 2017, and winter 2016–2017 glacier terminus position from reference; Joughin et al., 2017) to delineate the frontal zone of the Jakobshavn Isbræ in Ilulissat Icefjord, the glacier located in the only natural World Heritage site encompassing part of Greenland.

In order to investigate how future glacier evolution and possible disappearance will modify or jeopardize the OUV of the World Heritage sites that contain them, we analyzed the consideration of glaciers in official documents of inscription and in the statements of OUV. We found four different types of consideration for glaciers: (1) Glaciers were (among) the primary reasons for OUV, (2) they influence the wider OUV of the site, (3) they are recognized, but the site was inscribed only under biodiversity criteria, and (4) they are present but not recognized within OUV. A potential glacier decline will thus have no to crucial influence on the site's OUV and, hence, on the justification of the World Heritage status of a site.

2.3. Glacier Modeling

As illustrated for Southern Patagonia (Figure S1), some World Heritage glaciers only have small portion of their surface within the inscribed area. We thus removed the glaciers having less than 50% of their surface within the World Heritage sites to obtain a representative picture of the processes that will occur within the World Heritage sites. Hence, 18,452 World Heritage glaciers of the 19,039 inventoried (i.e., 97%) were considered during the glacier evolution modeling.

In order to assess the future evolution of all individual glaciers of the World Heritage, we rely on the established glacier model GloGEM (Huss & Hock, 2015). GloGEM computes glacier mass balance and associated changes in glacier geometry (thickness, length, and width) at the glacier-specific scale. The model operates in elevation bands of 10 m for each individual glacier. The surface mass balance is computed at monthly resolution as the sum of snow accumulation, snow, and ice melt and refreezing based on near-surface air temperature and precipitation time series. GloGEM also accounts for mass losses at marine- or lake-terminating glacier fronts due to iceberg calving and subaerial ablation approximated by a simple scheme (Oerlemans & Nick, 2005) that has been compared to direct observations in different regions of the Earth (Huss & Hock, 2015). At the end of each year, computed glacier mass changes are used to adjust each glacier's thickness distribution and spatial extent using an empirical parameterization relating total mass change to distributed ice surface elevation changes (Huss et al., 2010). The model thus does not explicitly include ice dynamics but parametrizes the corresponding effects on glacier geometry relying on a simple but widely used scheme (e.g., Li et al., 2015; Seibert et al., 2018). GloGEM was calibrated at the scale of individual regions of the RGI based on glacier mass change estimates derived from a multimethod consensus study (Gardner et al., 2013). Model results were compared to observations of glacier mass balance (in situ and geodetic measurements) available for all regions around the globe (Zemp et al., 2012) and glacier area changes indicating a generally good skill in reproducing past variation in glacier mass and area. For further details on the model, its calibration and downscaling procedures we refer to Huss and Hock (2015).

For the present study, the setup of GloGEM is widely consistent with the model version presented in Huss and Hock (2015). However, all model runs where updated using (i) the newest version of the RGI, that is, RGIv6.0, instead of RGIv4.0 as in Huss and Hock (2015), and (ii) time series of observed meteorological conditions were extended up to 2016. For some regions, this update has resulted in more accurate results for regions with an enhanced quality of glacier inventory data (e.g., central Asia), and for small glaciers experiencing large changes in the first decade of the 21st century.

2.4. Uncertainties

The results presented here are subject to uncertainties. First, except for Jakobshaven Isbrae (Ilulissat Icefjord, Greenland), the present World Heritage glacier inventory fully relies on the glacier outlines contained in the RGI. In some regions, glacier outlines are outdated. For instance, the nine glaciers of Yellowstone National Park listed in the RGIv6.0 seem to have disappeared already and/or are stagnant snow patches according to recent aerial photographs (imagery from *Google Earth* and *Plans* software). Our model also provides evidence for the likely disappearance of these glaciers by simulating complete glacier disintegration before 2005 (Figure S2). Nevertheless, the RGI remains the most complete source of glacier outlines at the global scale. In addition, we also analyzed aerial photographs in other natural World Heritage sites located in cold and mountainous environments to investigate if all World Heritage glaciers were included in the RGI. No large glaciers were found. However, existing remnant ice patches (e.g., in Pirin National Park, Gachev et al., 2016) or active rock glaciers (e.g., in Jiuzhaigou Valley Scenic and Historic Interest Area; 32°55′50″N, 103°53′E) having a potentially glacial origin (Berthling, 2011; Bosson & Lambiel, 2016) could indicate *recent* disappearance of active glaciers in a few World Heritage sites other than the 46 inventoried ones with glaciers.

Uncertainties also arise in projections of future glacier change using GloGEM from uncertainties in (1) the climate projections, (2) the data on initial glacier area and ice thickness, and (3) the simplifications and approximations in the model and the calibration procedure. Various sensitivity experiments performed by Huss and Hock (2015) have shown that factors (2) and (3) can importantly influence projected future glacier change of individual glaciers as no measurements of glacier-specific ice thickness are available at the global scale, many physical processes have to be strongly simplified in a global glacier model, and the downscaling

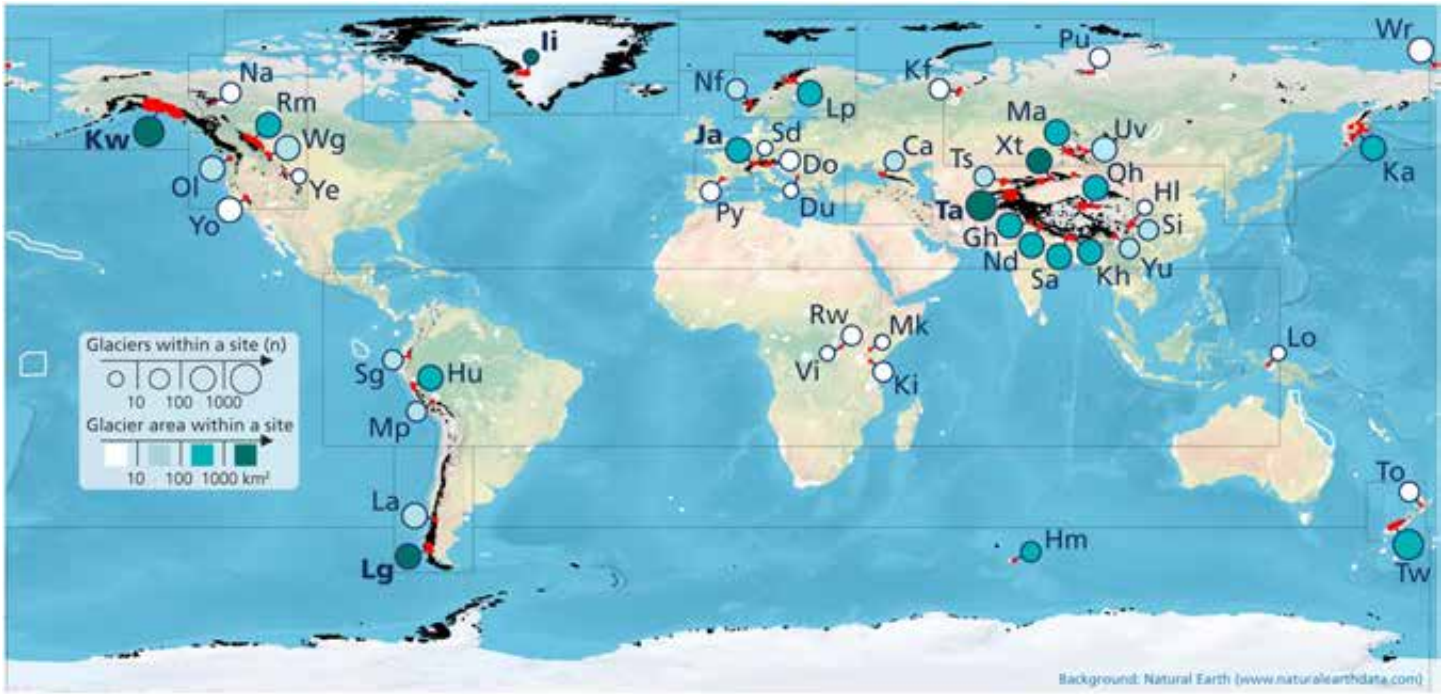

Figure 1. Glaciers (red dots) located in natural World Heritage sites (white polygons). Their number and area are scaled with circle size and color, respectively. Site names are abbreviated, and their full names are given in Table S2. Sites abbreviated in bold are those where glaciers were one of the primary reasons for inscription on the World Heritage List. Gray polygons are glacierized regions, and black dots correspond to all other inventoried glaciers (RGI Consortium, 2017, in addition to the two continental ice sheets in Greenland and Antarctica).

of meteorological variables to thousands of glaciers remains challenging. Nevertheless, validation of computed initial ice thicknesses and past mass balances against globally almost complete data bases of these variables has indicated a satisfactory performance of the model with only small regional biases (Huss & Farinotti, 2012; Huss & Hock, 2015). However, uncertainties in future climate forcing as evidenced by the partly large differences in projected temperature and precipitation changes of the individual global circulation models forced by the same CO_2 emission pathways are considerable and clearly dominate the overall uncertainties of the modeled glacier volume evolution of the 21st century (Marzeion et al., 2018). Here, we therefore consider uncertain climate evolution as the main uncertainty source and have used this factor to visualize and estimate overall uncertainty of glacier evolution in response to each RCPs.

3. Results

3.1. World Heritage Glaciers Inventory

We find that 19,039 glaciers have their whole or partial area within natural World Heritage sites. This corresponds to 9% of all glaciers on Earth (Figure 1 and Tables S2 and S3). Between one and several thousand glaciers, whose sizes range from 0.01 to 10^6 km^2, have been inventoried in 46 sites. Glaciers cover 55,950 km^2 within these sites, corresponding to 0.4% of the global glacier area (7.5% if one excludes the ice sheets in Antarctica and Greenland). New Zealand (76%; Table S1), Alaska (44%), and North Asia (26%) are the regions with the largest proportion of ice within World Heritage sites while Arctic Canada, Iceland, Svalbard, the Russian Arctic, and Antarctica have no World Heritage glaciers. Among outstanding glaciers, one of the fastest glaciers and largest iceberg producer (Jakobshavn Isbrae in Ilulissat Icefjord), the longest glacier outside continental ice sheets (Bering Glacier in Kluane Wrangell St Elias Glacier Bay Tatshenshuni-Alsek), and the highest glacier (on Mount Everest in Sagarmatha National Park) are designated as World Heritage. The largest glacier of Alaska (Seward Glacier in Kluane), central Europe (Grosser Aletschgletscher in Swiss Alps Jungfrau-Aletsch, Figure 2), central Asia (Fedchenko Glacier in Tajik

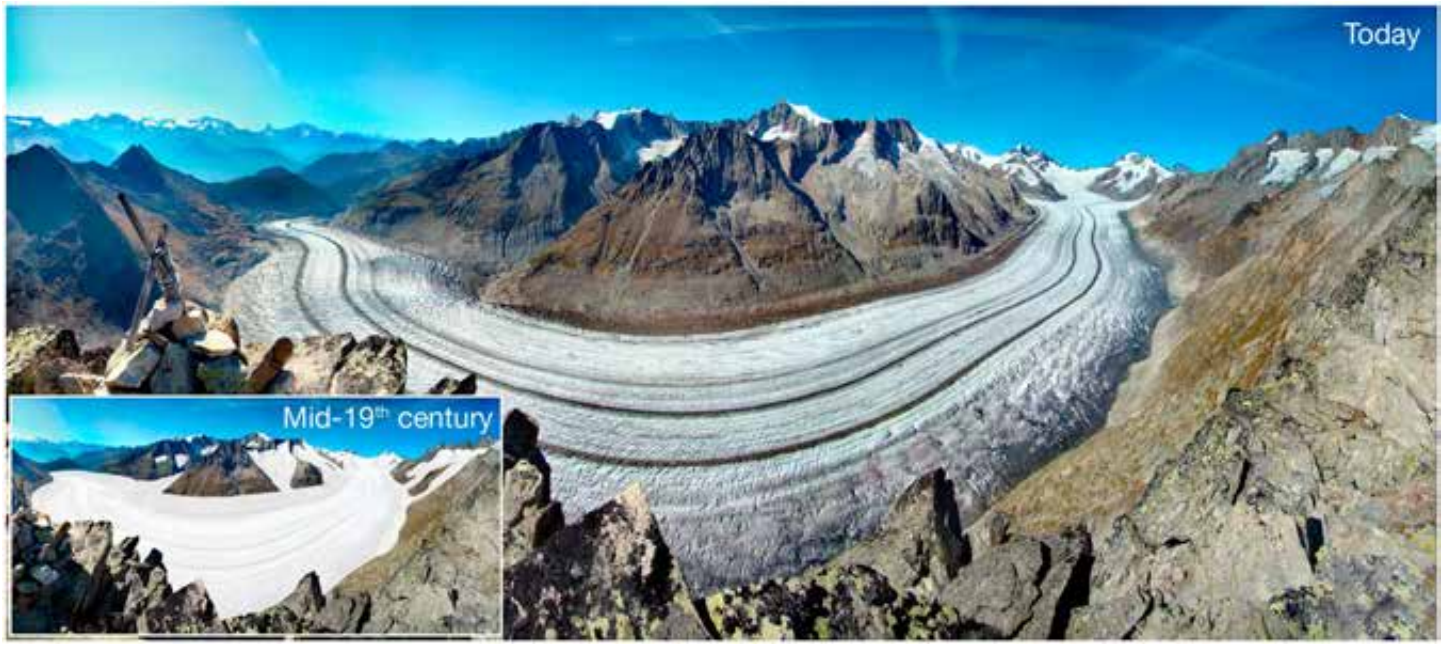

Figure 2. Current state and reconstitution of Grosser Aletschgletscher extent at the end of the Little Ice Age, in the midnineteenth century. This 23-km-long valley glacier is located in the World Heritage site Swiss Alps Jungfrau-Aletsch. It contributed significantly to the recognition of the World Heritage criteria vii (i.e., *aesthetic value*) and viii (i.e., *geological value*) that led to the inscription of this site in 2001. Grosser Aletschgletscher is by far the largest and longest glacier in the European Alps. It has lost more than 25% of its volume and has been partly dislocated since the midnineteenth century (Bauder et al., 2007). Illustrating the *long* response time of large glaciers to the post–Little Ice Age anthropogenic warming, Jouvet et al. (2011) showed that ~40% of its current volume would melt in future decades even if the climate would stabilize at the level of the year 2000. We project the melt of 66 ± 32% (RCP2.6) to 96 ± 7% (RCP8.5) of the current ice volume for this site by 2,100 (Table S4 and Figure S2), which will severely jeopardize its Outstanding Universal Value. Photograph: ©aletscharena.ch—Christian Rueegg, 2011. RCP = Representative Concentration Pathways.

National Park), Southern Andes (Pio XI in Los Glaciares National Park), and New Zealand (Tasman Glacier in Te Wahipounamu) are also listed.

The presence of glaciers is stated among the principal reasons for World Heritage inscription in five of the 46 sites (Table S2): Ilulissat Icefjord (Greenland), Kluane (Alaska), Los Glaciares National Park (Patagonia), Swiss Alps Jungfrau-Aletsch (Europe, Figure 2), and Tajik National Park (central Asia). In another 28 sites, glaciers contribute, together with other natural features, to their recognized OUV. In 13 sites, glaciers are not specifically mentioned as contributing to inscription.

3.2. Recent and Future Evolution of World Heritage Glaciers

Glaciers are among the best climate indicators in nature because their volume depends on air temperature, precipitation and energy exchange at the Earth's surface. Since the nineteenth century, by limiting snow precipitation and extending and intensifying melt periods, anthropogenic global warming has induced a worldwide glacier decline (Intergovernmental Panel on Climate Change, 2013; Marzeion et al., 2014; Zemp et al., 2015). Substantial ice loss with mostly increasing magnitudes since the 1990s affected World Heritage glaciers (e.g., Figure 2; Brun et al., 2017; Das et al., 2014; Kjeldsen et al., 2015; López-Moreno et al., 2016; Schaefer et al., 2015; Thompson et al., 2011). The largest one, Jakobshavn Isbrae, very likely experienced the most severe loss since the nineteenth century as surface and submarine ablation, ice flux and iceberg discharge noticeably increased. It accounted for ~6% of the Greenland ice loss between 1983 and 2003 (Kjeldsen et al., 2015) and for ~3% of global sea level rise between 2000 and 2011 (i.e., 1 mm, Howat et al., 2011). Retreat and thinning of other World Heritage glaciers locally led to their disintegration or even complete disappearance (e.g., López-Moreno et al., 2016; Thompson et al., 2011). Glaciers also likely disappeared recently in a few other World Heritage sites than those inventoried, as evidenced by remnant ice patches (e.g., Gachev et al., 2016). Within this period of overall decline, mass gain and glacier advances may have temporally and locally occurred at some of the sites (Mackintosh et al., 2017; Schaefer et al., 2015; Zemp et al., 2015),

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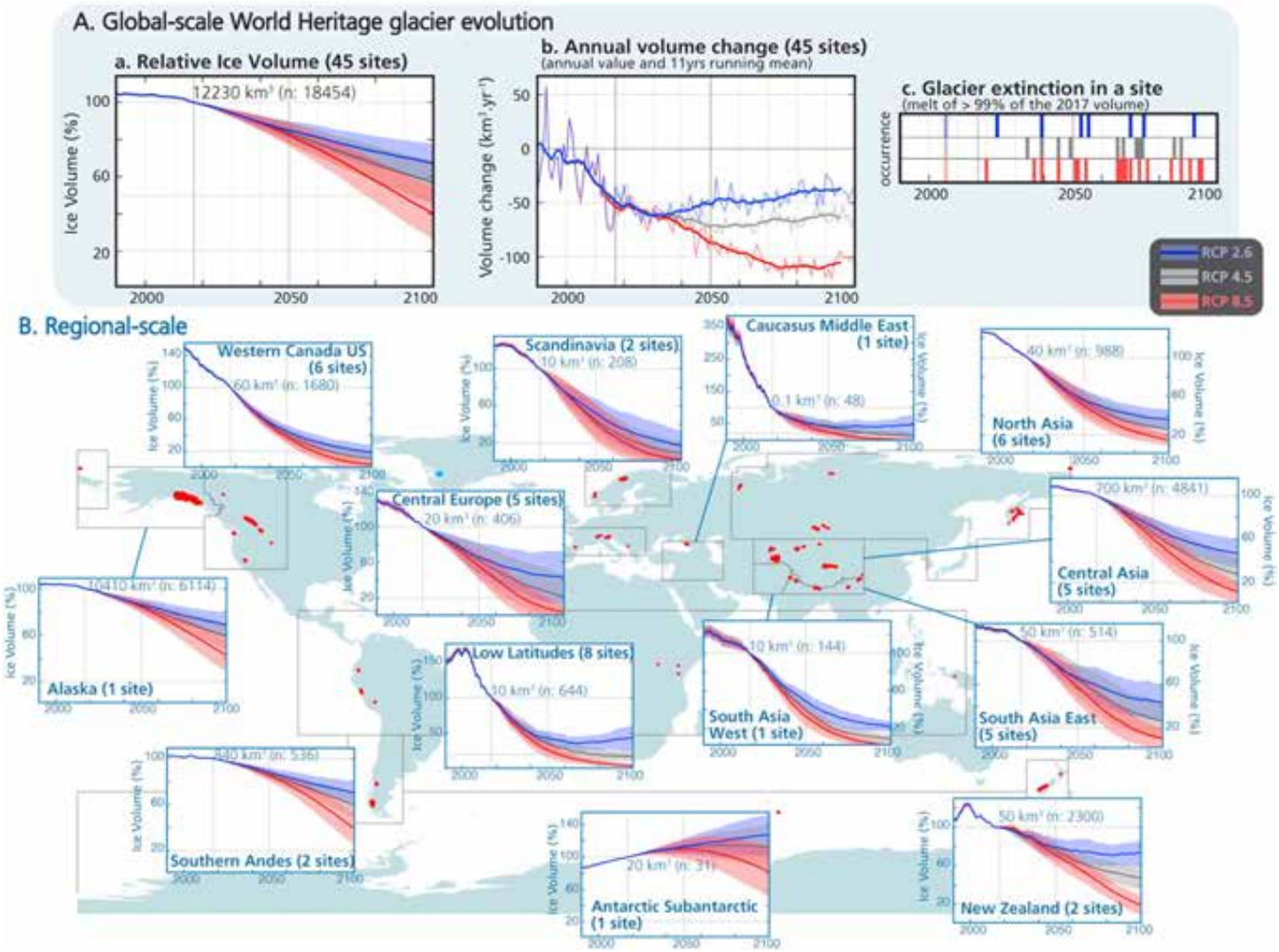

Figure 3. (a) Global and (b) regional 21st century evolution of glaciers located in natural World Heritage sites according to different CO_2 emission scenarios (RCP2.6, RCP4.5, and RCP8.5). Ice volume variations (multimodel mean of 14 general circulation models ±1 standard deviation) are relative to the 2017 ice volume (in cubic kilometer with the number of glaciers considered in each evolution diagram). On the map, the red dots correspond to the modelled World Heritage glaciers. RCP = Representative Concentration Pathways.

as a result of shorter-term decreases of atmospheric or oceanic temperatures, increases in precipitation, or variations of solar or volcanic activity.

We used a process-based model (Huss & Hock, 2015) to investigate the 21st century evolution of World Heritage glaciers. However, this model was not operable on Jakobshavn Isbrae due to the complexity of the involved glaciological and oceanographic processes for this site. According to existing modeling based on RCP4.5 (Church et al., 2013), this glacier will remain one of the largest contributors to sea level rise with 4–10 mm until 2100 (i.e., ~1% to 2.5% of the average global value). As the whole Greenland ice sheet, it responds with inertia to climatic variations and mass loss will very likely continue far beyond the end of the 21st century.

Overall, our model predicts a substantial ice loss for World Heritage glaciers throughout the 21st century (Figure 3a and Table 1). Mass loss by 2100 will account for 33 ± 11% (RCP2.6) to 60 ± 14% (RCP8.5) of the 2017 volume, corresponding to 3,600 ± 1,200 to 6,600 ± 1,600 km^3 of water, or 10 ± 3 to 18 ± 4 mm of sea level equivalent. All the annual (Figure 3a-b) and decadal means (Table 1) of glacier volume change are expected to be negative over the century, illustrating a continuous ice loss for all climatic scenarios.

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Table 1
Multimodel Means of the Computed Evolution of Glaciers Located in Natural World Heritage Sites Over the 21st Century

		RCP2.6	RCP4.5	RCP8.5
WH glaciers considered in the modelling (*n*)			18,452	
Ice volume (km^3)	2017	12,200	12,200	12,200
	2050	10,400 ± 600	10,200 ± 800	10,100 ± 800
	2100	8,200 ± 1,300	6,900 ± 1,500	4,900 ± 1,700
Relative volume change (%)	2017–2050	−15.1 ± 5	−16.2 ± 6.2	−17.6 ± 6.3
	2017–2100	−32.8 ± 10.7	−43.4 ± 11.9	−59.8 ± 14.1
Mass loss (Gt)	2017–2100	3,600 ± 1,200	4,800 ± 1,300	6,600 ± 1,600
Sea level equivalent (mm)	2017–2100	10.0 ± 3.3	13.2 ± 3.6	18.2 ± 4.3
Average annual volume change by decades (km^3/year)	2010–2020	−45	−48	−51
	2020–2030	−58	−57	−57
	2030–2040	−60	−61	−64
	2040–2050	−53	−67	−78
	2050–2060	−47	−72	−93
	2060–2070	−49	−71	−101
	2070–2080	−45	−65	−110
	2080–2090	−39	−63	−109
	2090–2100	−38	−63	−104
NWHS with ice melt >80% (*n*)	2017–2100	20	33	41
NWHS with ice melt >99% (*n*)	2017–2100	8	12	21
Glacier area (km^2)	2017	52,680	52,680	52,680
	2100	37,100 ± 5,200	31,600 ± 5,800	23,500 ± 6,900
Relative area change (%)	2017–2100	−29.6 ± 9.8	−40.0 ± 11.1	−55.4 ± 13.1

Note. Mass loss and sea level equivalent are computed assuming an ice density of 900 kg/m^3 and an ocean area of 3.625×10^8 km^2. WH = World Heritage. NWHS = Natural World Heritage sites.

However, the rate of mass loss will be reduced after the 2030s for RCP2.6 whereas it is expected to strongly increase for RCP8.5.

Due to heterogeneous climatic and topographic conditions, the evolution of World Heritage glaciers will differ at regional and site scales (Figures 3b and 4 and S2 and Tables 1, S4, and S5). However, except for the mostly balanced conditions modeled for Heard and McDonald Islands (Antarctic Islands), substantial ice loss will occur in all natural World Heritage sites. Over the 21st century, the magnitude of the relative ice melt will strongly depend on the size of glaciers in each site. Very small glaciers rapidly respond to climatic variations because it strongly modifies their mass balance and the accumulation area ratio (AAR, i.e., the ratio of the area of the accumulation zone compared to the entire glacier area, Figure 4). Hence, relative

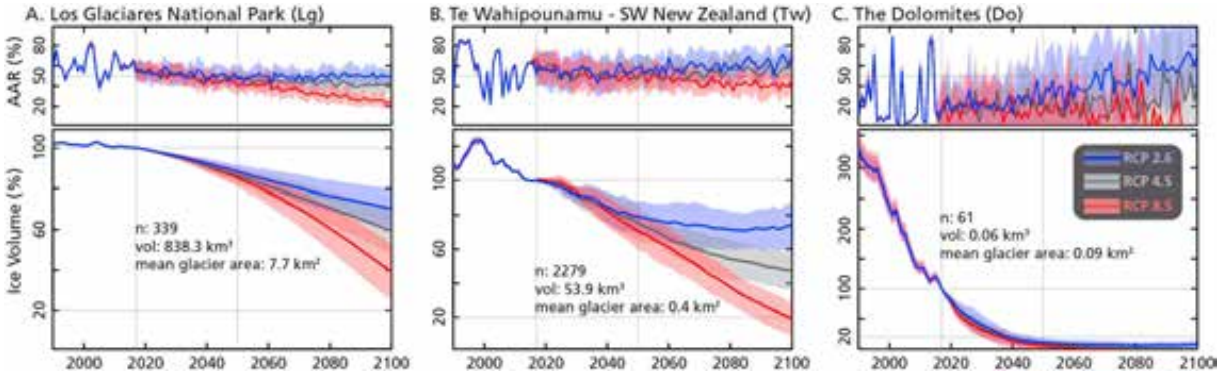

Figure 4. The 21st century evolution of glaciers located in three natural World Heritage sites according to different CO_2 emission scenarios (RCP2.6, RCP4.5, and RCP8.5). Ice volume variations (multimodel mean of 14 general circulation models ±1 standard deviation) are relative to the 2017 ice volume (in cubic kilometer with the number of glaciers and their mean area considered in each panel). Los Glaciares National Park (a; located in South America), Te Wahipounamu-SW New Zealand (b), and the Dolomites (c; central Europe) are displayed as examples of evolution in sites having mostly large ice cap glaciers, valley glaciers and very small glaciers, respectively. RCP = Representative Concentration Pathways; AAR = accumulation area ratio.

ice volume will rapidly decrease in sites with very small glaciers in a warming climate, while it will take longer in sites with large glaciers (Figure 4). If air temperature would stabilize in future decades as projected by RCP2.6, the smallest glaciers could rapidly find a new balance with climatic conditions and stop shrinking (AAR will be comprised between 50% and 70%) and even experience a mass gain if AAR values will exceed 70% as projected for the glaciers in Te Wahipounamu and the Dolomites (Figures 4b and 4c). Conversely, projections of glacier evolution in Los Glaciares National Park illustrate the slow response time of large glaciers (Figure 4a). The low AAR values (<50%) modeled for the glaciers in this site at the end of the 21st century indicate a strong imbalance between the remaining large ice volume and climatic conditions and thus the continuation of ice loss beyond 2100.

Overall, more than 80% of the 2017 ice volume is expected to have melted in 20 (RCP2.6) to 41 (RCP8.5) sites by 2100 and glacier extinction, defined here as the disappearance of more than 99% of the current ice volume, is forecasted in 8 (RCP2.6) to 21 (RCP8.5) sites (Figure 3a-c and S3 and Tables 1 and S4). Compared to ice volume in 2017, the difference between estimated volume losses by 2100 for RCP2.6 and RCP8.5 is smaller than 10% in 13 sites (e.g., Figures 4c and S3 and Table S4), reflecting the irremediable future vanishing of small glaciers in unfavorable environments. In other words, at such sites glaciers will disappear no matter which RCP scenario occurs. Conversely, this difference is above 25% in 20 sites (e.g., Figures 4a and 4b), emphasizing the strong influence of CO_2 emissions scenarios and, thus, human actions on the magnitude of ice loss. At the end of the century, the computed glacier geometry will be close to equilibrium with climate for RCP2.6 (mean AAR > 50% in 60% of the sites; e.g., Figures 4b and 4c and S4 and Table S4). However, a strong imbalance is modeled for RCP4.5 and RCP8.5 (mean AAR > 50% in only 31% and 3%, respectively, of the sites) and therefore suggests the continuation of ice loss far beyond 2100.

4. Discussion and Conclusion

Through the first complete inventory of glaciers located in natural World Heritage sites, the analysis of their recent evolution, and the modeling of their future mass change, this study shows that, beyond the presence of many outstanding glaciers and their particular internationally recognized World Heritage status, these glaciers are similar and representative of the other glaciers on Earth. From very small cirque glaciers to ice caps or part of the continental ice sheet, all types and sizes of glaciers can be found among the 19,039 World Heritage glaciers. Present in most of the glacierized regions on Earth (Pfeffer et al., 2014), they experienced the same widespread mass loss as other glaciers in response to recent anthropogenic warming (e.g., Zemp et al., 2015). Our projections on the intensification of their melt over the 21st century are in line with previous glacier modeling studies at the local, regional or global scale (e.g., Clarke et al., 2015; Kraaijenbrink et al., 2017; Marzeion et al., 2018; Radić et al., 2014; Zekollari et al., 2014). In comparison to a previous application of the global glacier model used in the present study (Huss & Hock, 2015), we find similar trends in glacier wastage, but results are based on the newest available input data and, hence, are assumed to be more accurate.

This ongoing major and unprecedented glacier decline highlights the threat posed to the World Heritage in a changing climate. The presence of glaciers has been recognized as a natural value and is often mentioned to justify the inscription of the 46 studied sites on the World Heritage list (Table S2). Hence, the strong ice loss, and moreover, the projected glacier extinction in 8 (RCP2.6) to 21 sites (RCP8.5) over the 21st century will strongly affect the integrity and value of many of these World Heritage sites. It could even directly question the recognized OUV in sites like Swiss Alps Jungfrau-Aletsch (Figure 2), Ilulissat Icefjord, or Kluane Wrangell St Elias Glacier Bay Tatshenshuni-Alsek, which have been inscribed at least partly for their exceptional glaciers.

These results complete the observations and projections made on the loss of other geological and biological assets in natural World Heritage sites in a warming climate (e.g., Allan et al., 2017; Hughes et al., 2017; Osipova et al., 2017; Scheffer et al., 2015). Despite their commitment to use utmost resources, states and international community fail to preserve and conserve some valued natural features for future generations, even in the most outstanding protected areas. The current situation of the Great Barrier Reef demonstrates the complexity of nature conservation in World Heritage sites in a changing climate. The World Heritage Committee considered inscribing this site as *in danger* as of 2015, due to the occurrence of climatically controlled coral bleaching events. To prevent this undesirable inscription, the Australian government adopted a

long-term sustainability plan (Normile & Dayton, 2014). However, the most serious bleaching event of at least 20 years occurred in 2016 (Hughes et al., 2017), illustrating that local and national efforts, as well as usual nature conservation tools, cannot address a global issue having the magnitude and the complexity of atmosphere and ocean warming. Loss and damage related to anthropogenic climate change could thereby lead to the designation of more and more World Heritage sites as *in danger* or with a *critical state of conservation* in the near future (Osipova et al., 2017). However, if the World Heritage status does not protect from climate change impacts, World Heritage sites currently serve to develop knowledge, mitigation, and adaptation policy and to raise public awareness of this issue. Increasing efforts are especially made since 2005 by the different involved stakeholders in terms of strategy and capacity building from the local to the global scale (e.g., United Nations Educational, Scientific and Cultural Organization, 2014).

In an increasing number of publications (e.g., Ceballos et al., 2017; Hughes et al., 2017; Intergovernmental Panel on Climate Change, 2018; Ripple et al., 2017; Steffen et al., 2018), the scientific community warns humanity against the critical state of climate, nature, and societies on Earth in the Anthropocene and shows that decisive actions have to be urgently taken to prevent unprecedented, damageable, and irreversible consequences. In this context and among other actions, World Heritage glaciers conservation could be both used as a leverage and a target for planetary-scale climate change mitigation. Indeed, the safeguarding of these iconic and important natural features could mobilize global-scale conservation and mitigation benefits. As for all glaciers and ice sheets on Earth, their preservation reinforces the compelling priority for strong and rapid reduction of greenhouse gas emissions and thereby a deep modification of human impacts on the climate. World Heritage glaciers are thus analogous to *umbrella species* (Simberloff, 1998), and their conservation will automatically allow and imply the conservation of other features threatened by global warming. As all glaciers and ice sheets, World Heritage glaciers have also the characteristics of *keystone species* (Simberloff, 1998) because of their disproportionately large impacts on nature and societies on Earth. Glaciers and ice sheets have an important influence on global climate and sea level (e.g., Intergovernmental Panel on Climate Change, 2013; Marzeion et al., 2018; Marzeion & Levermann, 2014; Steffen et al., 2018). In many regions, they strongly impact freshwater, sediment and biogeochemical fluxes, biodiversity, and geohazards and provide many *nature's contributions to people* (e.g., Díaz et al., 2018; Huss et al., 2017; Huss & Hock, 2018; Milner et al., 2017). Their vanishing will thus have significant natural, social, economical, and migratory cascading consequences and could contribute to push and lock our planet beyond a threshold where the Earth would become a dangerous and uncontrollable hothouse (Steffen et al., 2018). Endangered World Heritage glaciers are finally similar to *flagship species* (Simberloff, 1998) because these emblematic and sensitive features have a large potential to raise global awareness, especially in view of the clear international commitment to protect World Heritage sites from damage or loss.

All of this emphasizes the compelling need and opportunity to act against worldwide (World Heritage) glacier decline. Supporting recent findings (Marzeion et al., 2018), our results show how drastic reductions of emissions (notably the achievement of RCP2.6) will rapidly curb melt rates to safeguard a large glacier volume in the long-term, limiting sea level rise and other cascading consequences. Within this scope, individual and collective actions (e.g., Intergovernmental Panel on Climate Change, 2014, 2018; Ripple et al., 2017; Wynes & Nicholas, 2017) are proposed to achieve the rapid and far-reaching societal transition required to respect the commitments made during the first worldwide climate agreement in 2015 in Paris.

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Projected deglaciation of western Canada in the twenty-first century

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Retreat of mountain glaciers is a significant contributor to sea-level rise and a potential threat to human populations through impacts on water availability and regional hydrology. Like most of Earth's mountain glaciers, those in western North America are experiencing rapid mass loss[1,2]. Projections of future large-scale mass change are based on surface mass balance models that are open to criticism, because they ignore or greatly simplify glacier physics. Here we use a high-resolution regional glaciation model, developed by coupling physics-based ice dynamics with a surface mass balance model, to project the fate of glaciers in western Canada. We use twenty-first-century climate scenarios from an ensemble of global climate models in our simulations; the results indicate that by 2100, the volume of glacier ice in western Canada will shrink by 70 ± 10% relative to 2005. According to our simulations, few glaciers will remain in the Interior and Rockies regions, but maritime glaciers, in particular those in northwestern British Columbia, will survive in a diminished state. We project the maximum rate of ice volume loss, corresponding to peak input of deglacial meltwater to streams and rivers, to occur around 2020–2040. Potential implications include impacts on aquatic ecosystems, agriculture, forestry, alpine tourism and water quality.

Recent global-scale estimates using simple models (for example, refs 3–6) indicate that mountain glaciers could raise sea level by 0.39 m by 2100 (ref. 7). At regional-to-local scales efforts to project glacier mass changes have varied from models that apply glacier dynamics configured for single ice masses (for example, refs 8,9) to those with greater geographical extent that rely on empirical scaling[10,11], scaling in combination with a low-order treatment of ice dynamics[12–14] or sub-grid parameterizations[15]. At these spatial scales the main effects of deglaciation are associated with changes in the hydrologic cycle[16,17] and consequent impacts on water availability, aquatic habitat, hydroelectric power generation, recreation and tourism.

Projections of glacier surface mass balance (accumulation and ablation) can reveal the ultimate fate of glaciers, but they lack information on rates of change of thickness and extent. Glaciers individually respond to changes in the surface mass balance field and may survive an adverse climate by stabilizing at a higher elevation. This stabilization due to changes in glacier hypsometry (ice area altitude distribution) has been represented through scaling empiricisms in all current models of glacier evolution on regional and global scales[5,6,8,15]. A common feature of these models is that they lack a physics-based treatment of glacier dynamics. The central contribution of our study is thus to simulate the changes in ice thickness and extent over a large region using a high-resolution model of glacier dynamics, which yields year-to-year changes in ice area and volume for the entire study region.

Our study area is Alberta and British Columbia (BC) in western North America (Fig. 1), where glaciers account for an estimated area of 26,700 km^2 (ref. 18) and volume of 2,980 km^3 (ref. 19). The geographical scale is comparable to that of other glacierized mountain regions, such as South America (∼31,900 km^2; ref. 7), the Himalaya and Karakoram (∼22,800 km^2 and ∼18,000 km^2; refs 16,20) and Tien Shan (∼16,400 km^2; ref. 21), where declining glacier melt will impact populations. In this study we project the evolution of regionally resolved glaciers from the present to 2100, using a regional glaciation model (RGM; Methods and Supplementary Sections 1 and 2): a high-resolution (200 m) glacier surface mass balance model coupled to a physics-based model of glacier dynamics. Projections are cast in the modelling framework of the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5; ref. 7) and use climate projections from six well-performing General Circulation Models (GCMs; refs 22,23) forced by the four AR5 emissions scenarios. These scenarios, referred to as representative concentration pathways (RCPs), are labelled RCP2.6, RCP4.5, RCP6.0 and RCP8.5, where the numbers indicate the increase in radiative forcing (W m^{-2}) by 2100 relative to pre-industrial values.

Model skill can be assessed by comparing ice hypsometry from a 2005 inventory with modelled results from the same year (Fig. 2), as well as by comparing the number and area of observed and modelled ice masses (ref. 18 and Supplementary Table 3). The model is spun up from an ice-free state at year 0 to reach a quasi-steady state at 1901; subsequently, historical (1902–1979) and reanalysis (1980–2008) climate data are used (Methods and Supplementary Section 2.1). A comparison between spin-ups using steady and stochastic forcing confirms that by 1980 both procedures lead to the same result. Applying the observations of ice extent to a digital elevation model (DEM; Supplementary Section 1) together with an estimate of subglacial topography[19] allows modelled and estimated volumes to be compared. The area comparisons show fractional errors of +17.8% for the Coast, −3.6% for the Interior, −2.9% for the Rockies and +14.1% for All. The fractional discrepancy between modelled and estimated ice volume (Supplementary Table 3) can be large (+60.7% for All), but the influence of these errors on

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Figure 1 Study region and subregions in the Canadian Cordillera of western Canada. Present-day (2005) glacier extent is indicated in white. The yellow rectangle indicates the location of Columbia Reach drainage basin. Inset: Study region (black rectangle) within northwestern North America.

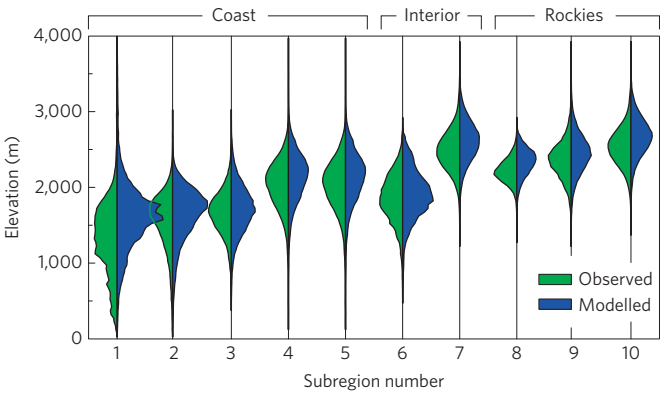

Figure 2 Comparisons of observed and modelled ice hypsometry for reference year 2005. For each of the ten subregions, pairs of bell-shaped curves show the distribution of ice area (normalized to the largest observed area) with elevation for the observed (green) and modelled (blue) ice extent.

normalized projections of area and volume (Fig. 3) is surprisingly small (Supplementary Section 6 and Figs 41 and 44).

Large-scale projections of the model (Fig. 3) are summarized for the Coast, Interior, Rockies and All regions. Glaciers of the Coast region are most resistant to climate change. For these glaciers, depending on the scenario, the ensemble means indicate that, relative to 2005, 75 ± 10% of the 2005 ice area and 70 ± 10% of the volume will be lost by 2100 (here and throughout, error ranges are for model mean $\pm 1\sigma$). For the Interior and Rockies regions ice area and volume losses will exceed 90% of the 2005 amounts for all scenarios except RCP2.6. The resistance of Coast glaciers to climate-forced changes in area and volume is associated with subregions 1 (St Elias), 2 (Northern Coast) and 4 (Southern Coast), which have the highest present-day ice content (Supplementary Table 3). The remaining Coast subregions will experience total or near-total losses of ice area and volume. Comparison of area and volume projections for all GCMs and scenarios revealed that the MIROC-ESM GCM (Supplementary Table 1) most frequently represented the median member of the GCM ensemble. To examine the detailed spatio-temporal character of the model projection, we therefore identified six focus sites and extracted projection modelling time snapshots for the MIROC-ESM projections. The message that the magnitude of deglaciation will be significant does not differ from that of Fig. 3, but the visual consequences of ice loss are emphasized (Supplementary Figs 27–32).

The potential sea-level rise from glacier loss in the study region (6.3 ± 0.6 mm; ref. 19) is modest, but the hydrologic implications of the projected loss are substantial. As an example, the Columbia River, which flows from its headwaters in Interior BC to the Pacific Coast of Washington and Oregon, yields the largest hydroelectric production of any river in North America. The hydroelectric generating capacity of the Canadian headwaters exceeds 5 GW (ref. 24). In BC, the Columbia Reach drainage basin (Fig. 4a) is the most intensely glacierized part of the Columbia River Basin and thus the most susceptible to changes in ice cover. The main influence of glacier runoff in the Columbia River Basin is to maintain stream flow, which contributes water to the Mica Reservoir for hydroelectric power generation (Fig. 4a), and to regulate water temperature through summer months[25,26]. The Columbia River Treaty between Canada and the USA, signed in 1964 and renegotiable from 2024 onwards, provides a detailed framework for cooperation on hydroelectric power generation and flood control. Climate-forced changes in water availability will redistribute costs and benefits between the treaty partners.

The observed (Fig. 4a) and the modelled (Fig. 4b) Columbia Reach ice cover for 2005 broadly agree with the observed and modelled area (733 km^2 and 666 km^2) and volume (44 km^3 and 36 km^3). Widespread glacier loss occurs by 2050 (Fig. 4c), with near-total ice disappearance by 2100 (Fig. 4d) for the MIROC-ESM GCM and the RCP8.5 scenario. Using ice area and volume projection results from the six GCMs (Supplementary Table 1) and four AR5 scenarios, we present time series for the averages and $\pm 1\sigma$ ranges for the multi-model ensemble (Fig. 4e,f). Until mid-century (~2050), the fate of all glaciers in this area is virtually independent of the emission scenario and climate model used for the projections. By the end of the century, however, the ensemble averages range from ~70% (RCP2.6) to ~95% (RCP8.5) reduction of both area and volume relative to 2005 values. The rate of change in ice volume (Supplementary Section 4.5) for each GCM and the RCP2.6 (Fig. 4g) and RCP8.5 (Fig. 4h) scenarios yields the projected changes in meltwater input from glacier ice loss. The graphs clearly show the effect of an unsustainable 'deglaciation discharge dividend' (ref. 27). For the majority of GCMs and scenarios, runoff from glacier wastage is characterized as a well-defined peak in meltwater discharge, having a typical amplitude of ~15 $m^3 s^{-1}$, roughly 3% of the ~500 $m^3 s^{-1}$ annual average discharge of Columbia River at the Mica Dam, followed by decades of declining flow. Our simulated deglaciation discharge (Fig. 4g,h) supplements the annual cycle of glacier storage and melt, and corresponds to annual average rates of mass loss that would mainly occur in summer

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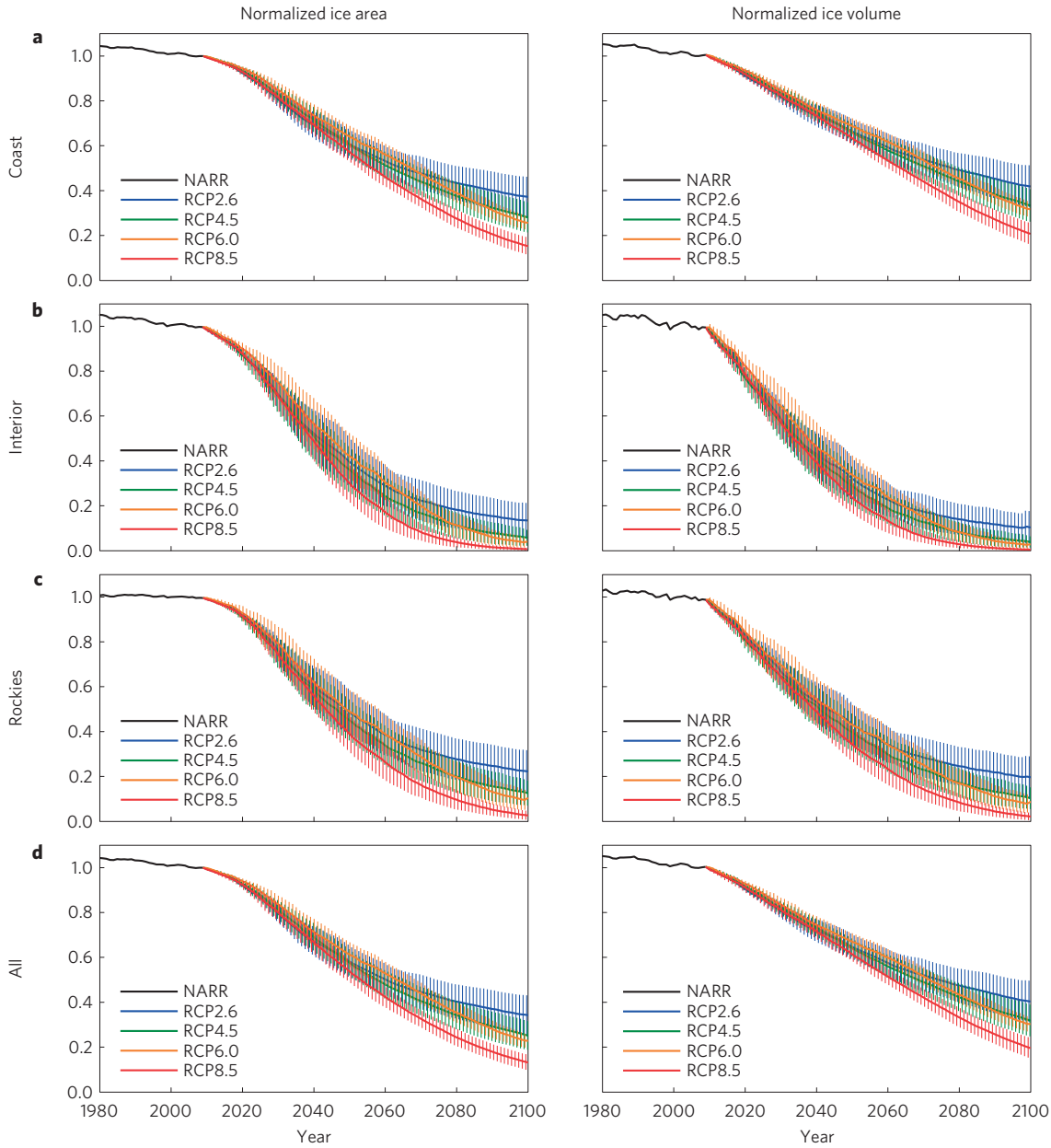

Figure 3 Projected changes for glaciers in the western Canadian study region. a–d, Area (left) and volume (right) are normalized to modelled values for the reference year 2005: projections for Coast glaciers (**a**), Interior glaciers (**b**), Rockies glaciers (**c**) and all glaciers (**d**). The mean (solid curves) and $\pm 1\sigma$ limits (vertical hatching) for the multi-model GCM ensemble are plotted for four different emissions scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5). NARR denotes the North American Regional Reanalysis.

and early fall. Meltwater discharge projections for all GCMs and scenarios and for all regions and subregions, as well as for the Canadian Columbia River Basin, are also calculated (Supplementary Sections 4.5 and 4.7). Most of these runs indicate a clear peak in discharge, in marked contrast to recent runoff projections[28] obtained using a model without ice dynamics that show no peak for western Canada.

Uncertainty in the RGM projections results from the uncertainty concerning which emissions pathway will be followed, from the range of GCM projections of future climate and from shortcomings of the surface mass balance model, the estimated subglacial topography and the ice dynamics model. Uncertainties associated with GCM projections are examined in the AR5 (ref. 7), but for mountainous regions additional uncertainty is contributed by orographic effects on precipitation and temperature[29] (Supplementary Section 2.2). Uncertainties associated with the mass balance model are dominated by the ensemble variability within each scenario rather than by limitations of the model. The error contribution of the ice dynamics model is small relative to that from the surface mass balance treatment (Supplementary Section 9). Our sensitivity analysis (Supplementary Tables 5–10) indicates that projections of ice area and volume have low sensitivity to reasonable parameter assignments for the ice dynamics model but high sensitivity to parameters of the surface mass balance model. Ice dynamics calculations increase the computational demands but do not greatly complicate the projection methodology. Projections performed with and without ice dynamics have been compared (Supplementary Section 7); when ice dynamics are neglected the RGM systematically underestimates ice volume loss at 2100 ($47 \pm 12\%$ loss without

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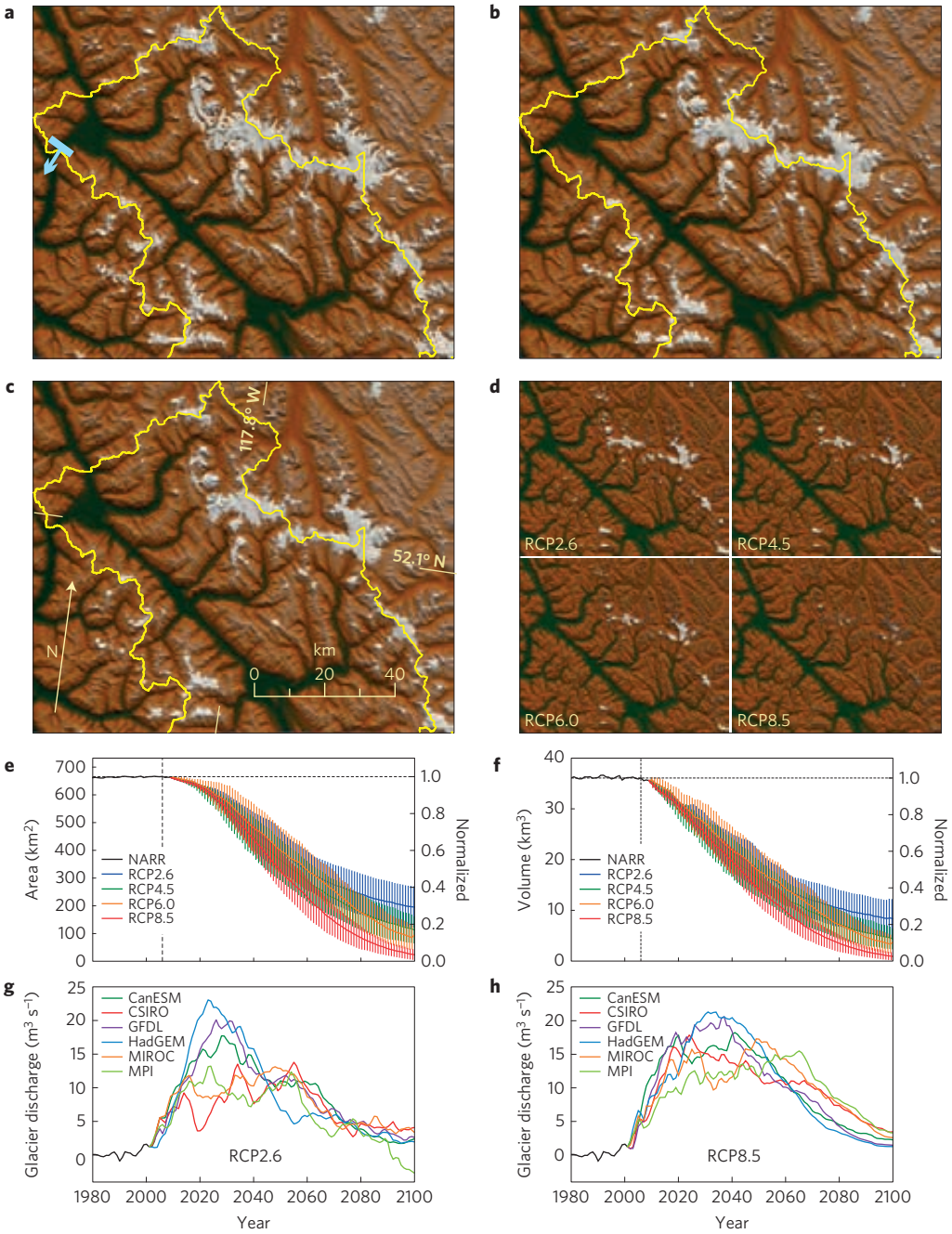

Figure 4 | Projected changes for glaciers in the Columbia Reach drainage basin within the Columbia River Basin of British Columbia. a,**b**, Observed (**a**) and modelled (**b**) glacier extent in the Columbia Reach drainage basin (yellow outline) for the reference year 2005. The Mica hydroelectric dam in the northwest quadrant is indicated by a light blue bar, with an arrow to indicate the water flow direction. **c**, Model projection for 2050 using MIROC-ESM with RCP2.6 forcing. The ice extents for RCP4.5, RCP6.0 and RCP8.5 (not shown) are virtually the same as for RCP2.6. **d**, Model projections for 2100 using MIROC-ESM with RCP2.6, RCP4.5, RCP6.0 and RCP8.5 forcings. **e**, Projected changes in ice area for the drainage basin. **f**, Projected changes in ice volume for the drainage basin. The graphs shown in **e** and **f** are for an ensemble of GCMs and four emissions scenarios; ensemble means are indicated by solid lines and the $\pm 1\sigma$ limits by vertical hatching. The relative changes (right ordinate) are normalized to the modelled values for the 2005 reference year. **g**, Projected changes in mean annual meltwater input from glacier ice loss for the RCP2.6 scenario and an ensemble of GCMs. **h**, Projected changes in mean annual meltwater input from glacier ice loss for the RCP8.5 scenario and an ensemble of GCMs. The maps show the northern half of the drainage basin, which contains ~85% of the present-day ice cover. The time series are the summed contributions for the entire basin.

dynamics and 60 ± 10% with dynamics for 'All' and RCP2.6; Supplementary Fig. 48). Comparisons of observed and modelled ice extents offer a powerful approach to refining surface mass balance fields, but one that is possible only using models that include dynamics. The effects of introducing a mass balance bias correction were carefully examined (Supplementary Section 6). The main challenge remains that of improving the surface mass balance treatment.

In addition to the hydrologic implications of reduced late-summer surface flows in the Columbia Basin, our projected changes of ice cover in western Canada have broader ramifications for aquatic ecosystems, agriculture, forestry, alpine tourism,

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water quality and resource development. Our study departs from previous large-scale projections of glacier response to climate change by including the contribution of ice dynamics and by operating at high spatial resolution despite the large size of the study region. By archiving the deglaciation projections for all the GCMs and scenarios for the entire study region (http://www.unbc.ca/research/supplementary-data-unbc-publications) we open the possibility for a wide range of local- and regional-scale impact studies. With appropriate modifications of the climate projections and surface mass balance models, the present work provides a template for an assessment of future mass change in Earth's other glacierized mountain regions.

Methods

The regional glaciation model (RGM) combines a surface mass balance model that quantifies mass fluxes (accumulation and ablation) at the glacier and land surfaces with an ice dynamics model to simulate ice flow (Supplementary Figs 2 and 3). Both models rely on gridded representations of the present-day surface elevation and ice extent. Data from the 2000 Shuttle Radar Topography Mission (available at http://srtm.csi.cgiar.org) were reprojected and resampled at a resolution of 200 m to obtain a DEM of surface topography; glacier outlines from around 2005 (available at http://www.glims.org/RGI) were used to derive a rasterized and co-registered ice mask. From these and other data, a DEM of the hidden subglacial topography was estimated using an optimization method (Supplementary Section 1.1).

The surface mass balance model calculates ablation by a distributed temperature-index model, accumulation using a temperature threshold to differentiate snow from rain precipitation and refreezing following a parameterized thermodynamic approach (Supplementary Section 2.3). To calibrate the model we force it with downscaled monthly climate fields derived from the North American Regional Reanalysis for 1980–2008 (NARR; ref. 30). NARR temperature and precipitation fields are downscaled from a horizontal resolution of 32 km to 200 m using methods described elsewhere[29]. Model calibration consists of tuning the model parameters to minimize a misfit between modelled and observed glacier mass balances derived from all available *in-situ* and geodetic measurements in the region within the period 1980–2008 (Supplementary Section 2.3). To obtain past and future forcings we take the downscaled NARR monthly averaged temperature and precipitation fields for 1980–2008 to represent the baseline of these fields and superimpose the anomalies from the CRU data set for 1902–1979, and from an ensemble of GCM outputs for 2009–2100 (Supplementary Section 2.5). Forced by these climate fields, the mass balance model yields annual mass balance fields at a resolution of 200 m for 1902–2100 which are then coupled with the glacier dynamics model. The coupling takes into account the feedback mechanisms between glacier mass balance and glacier geometry changes (for example, positive feedback between glacier thinning and mass balance; negative feedback between glacier shrinking and mass balance), while the dynamics model redistributes the mass through ice flow.

The glacier dynamics component of the RGM assumes the shallow-ice approximation and isothermal ice. The model is 2.5D (two-dimensional vertically integrated) with a grid spacing of 200 m. Evolution equations for surface elevation are approximated as finite-difference expressions and solved using a super-implicit numerical scheme and flux-limiters (Supplementary Section 1.2). The ice dynamics model is spun up from an ice-free state at year 0 by randomly selecting the modelled annual mass balance for each year in the range 1902–1931 and applying this forcing from year 0 to 1901, by which time a quasi-steady state ('stochastic equilibrium') is attained. Our simulations start from this modelled 1901 ice configuration, progress through the twentieth century to 2009, and are then projected from 2010 to 2100. Model skill is assessed by comparing the observed ice hypsometry from a 2005 inventory with modelled results for the same year. To improve the model skill, we apply a bias to the surface mass balance field, following similar bias-correction strategies as in other projection studies (for example, refs 3,6). The bias is additive, spatially varying and constant in time (Supplementary Section 2.7). RGM simulations forced with biased and unbiased mass balance fields exhibit differences in the total area and volume of modelled ice, but similar population statistics for glaciers modelled with and without the bias (Supplementary Section 6). Projection results for 2009–2100 for all GCMs and scenarios of our study are archived at http://www.unbc.ca/research/supplementary-data-unbc-publications.

Code availability. The code is not available.

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Author contributions

G.K.C.C., A.H.J. and F.S.A. co-developed the ice flow code used in this study. A.H.J. provided downscaled precipitation fields for the mass balance sub-model as well as numerical insights for the development of the overall model chain. F.S.A. developed the mass balance modelling framework. V.R. performed downscaling of CRU and GCM data, contributed to the development of the bias-correction methods and helped to guide the final write-up. B.M. led the research network, provided essential data sets and guided the final write-up. G.K.C.C. performed the final calculations and wrote the initial versions of the manuscript and supplement.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.K.C.C.

Competing financial interests

The authors declare no competing financial interests.

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Earth's Future

REVIEW

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Toward mountains without permanent snow and ice

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Key Points:
- Deglaciation of low- to mid-latitude mountain ranges is likely to occur within this century
- Strong impacts on hydrology, erosion rates, sediment and nutrient flux, as well as water quality, aquatic habitat and biotic communities will result
- Far-reaching implications for human adaptation to a world of mountains without permanent snow and ice

Supporting Information:
- Supporting Information S1

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Abstract The cryosphere in mountain regions is rapidly declining, a trend that is expected to accelerate over the next several decades due to anthropogenic climate change. A cascade of effects will result, extending from mountains to lowlands with associated impacts on human livelihood, economy, and ecosystems. With rising air temperatures and increased radiative forcing, glaciers will become smaller and, in some cases, disappear, the area of frozen ground will diminish, the ratio of snow to rainfall will decrease, and the timing and magnitude of both maximum and minimum streamflow will change. These changes will affect erosion rates, sediment, and nutrient flux, and the biogeochemistry of rivers and proglacial lakes, all of which influence water quality, aquatic habitat, and biotic communities. Changes in the length of the growing season will allow low-elevation plants and animals to expand their ranges upward. Slope failures due to thawing alpine permafrost, and outburst floods from glacier- and moraine-dammed lakes will threaten downstream populations. Societies even well beyond the mountains depend on meltwater from glaciers and snow for drinking water supplies, irrigation, mining, hydropower, agriculture, and recreation. Here, we review and, where possible, quantify the impacts of anticipated climate change on the alpine cryosphere, hydrosphere, and biosphere, and consider the implications for adaptation to a future of mountains without permanent snow and ice.

1. Introduction

Mountain environments have great topographic complexity, intertwined with linked physical and biological processes across steep vertical gradients. The mountain cryosphere (snow, ice, and permafrost) plays a critical role in these environments and is an important source of water to downstream regions. Seasonal and longer-term changes in the cryosphere regulate water, nutrient, and sediment supply to mountainous and downstream ecosystems and are crucial for multiple societal needs—agriculture, hydropower generation, drinking water supplies, recreation, and industry. Half of the world's population depends on mountain water, and anticipated future population growth is likely to further increase the pressure on water resources around the globe [*Beniston*, 2003].

Rising air temperatures over the past century have driven a reduction in the area and volume of glaciers, with deglaciation rates in high mountains accelerating in recent decades [*Bolch et al.*, 2012; *Rabatel et al.*, 2013]. A complete loss of glaciers in some low-latitude mountain ranges has already occurred [*Rabatel et al.*, 2013], accompanied by a shorter duration of seasonal snow cover [*Brown and Mote*, 2009] and widespread permafrost thaw [*Haeberli*, 2013]. As concentrations of greenhouse gases in the atmosphere continue to increase, average air temperatures are expected to rise further. Observations and model simulations point to particularly large temperature increases at high elevations, particularly at low latitudes [*Vuille et al.*, 2008;

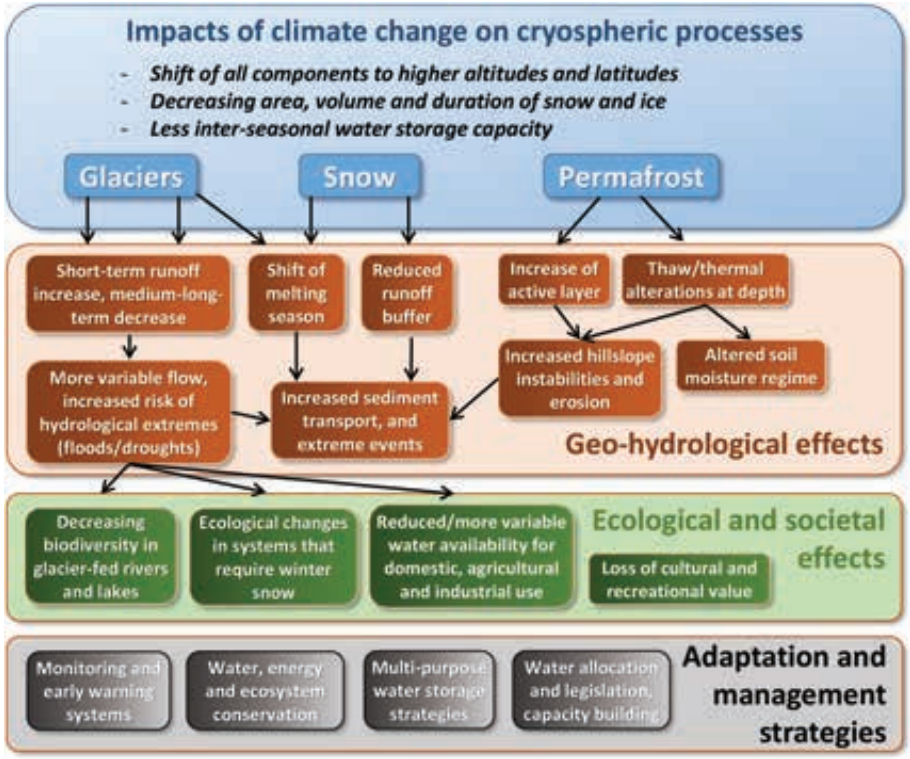

Figure 1. Summary of climate change impacts and process linkages within the mountain cryosphere.

MRI Working Group, 2015]. In addition, local and regional anthropogenic impacts, such as deposition of black carbon on snow and ice and the associated decrease in surface albedo, will have similar consequences [*Ramanathan and Carmichael*, 2008; *Xu et al.*, 2009]. Complex relations among cloud cover, solid and liquid precipitation, surface albedo, and net radiation will lead to further declines in glacier mass balance and the area of snow-covered terrain [*Painter et al.*, 2012]. As a consequence, we are in a transition phase from a world with glacierized mountains to a situation where permanent snow and ice cover is likely to be strongly reduced or even eliminated.

In this review paper, we assess the effect of the future decline of the mountain cryosphere, manifested in a series of cascading impacts on the natural and human systems that the cryosphere supports (Figure 1). Applying a global perspective, we consider the key hydrologic, geomorphologic, and ecological processes in which the mountain cryosphere plays a critical role. We quantify processes and mass fluxes that are presently relatively well understood and point to areas where a lack of quantitative measurements limits our understanding of potential future changes. Our review focuses on recent developments in quantifying present and future glacio-hydrological fluxes, as well as linking them to potential impacts on geomorphology, ecology, and society at the global scale, thus extending the scope of previous comprehensive reviews on this topic [e.g., *Beniston*, 2003; *Barnett et al.*, 2005; *Bolch et al.*, 2012; *Intergovernmental Panel on Climate Change*, 2013] on mountains and climate change.

2. Mass Fluxes Related to the Cryosphere and Mountain Hydrology

Figure 2 provides a schematic view of mountain systems and processes addressed in this paper. We quantify mass fluxes (*F*) and the mass of reservoirs (*M*) related to mountain hydrology at the global scale based on published literature. All fluxes are estimates that are subject to considerable uncertainties, which we do not discuss here. Below we summarize data, methods, and references used to quantify these fluxes.

We evaluate average total precipitation over the Earth's land surface area, except for Antarctica, for the period 1981–2010 based on several different data sets, including those of the Climatic Research Unit (CRU)

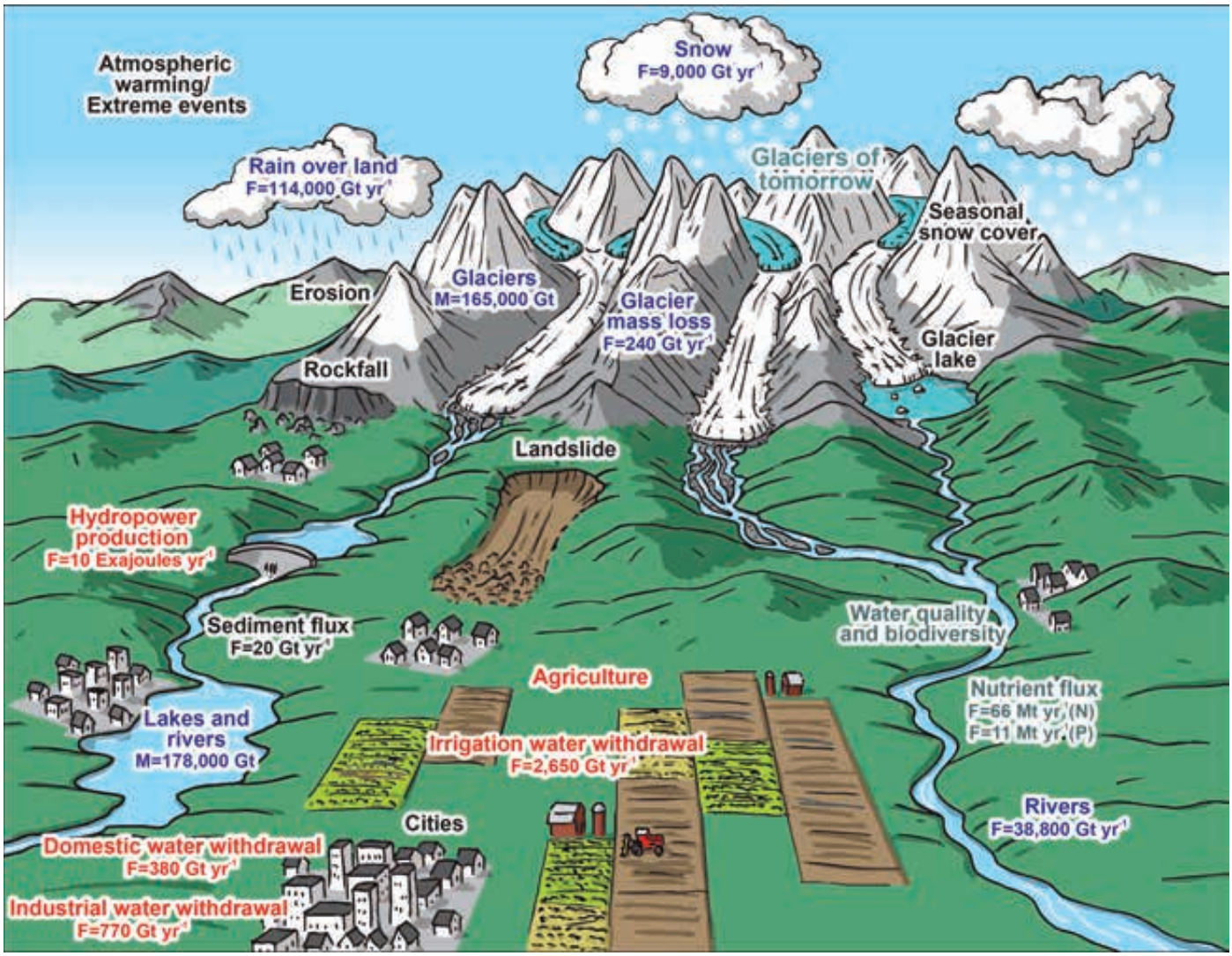

Figure 2. Schematic view of mountain systems and processes addressed in this paper. Estimates of mass fluxes (*F*) and the mass of reservoirs (*M*) refer to the global land surface.

[*Harris et al.*, 2014], the Global Precipitation Climatology Centre [*Schneider et al.*, 2011], and the University of Delaware [*Willmott and Matsuura*, 2001]. These data sets indicate a total precipitation flux over land of $F = 114{,}000\ \mathrm{Gt\ yr^{-1}}$, with a range of $\pm 9{,}000\ \mathrm{Gt\ yr^{-1}}$ among them. Solid and liquid precipitation has been separated using a threshold surface air temperature of 1°C. Temperature data have been provided by the CRU and the University of Delaware data set at monthly resolution and with areal cells of 0.5 × 0.5°, respectively. Snow precipitation over the Earth's land surface area except for Antarctica ($F = 9{,}000 \pm 500\ \mathrm{Gt\ yr^{-1}}$) also refers to the period 1981–2010.

The current mass of the roughly 200,000 glaciers on Earth, excluding the ice sheets in Greenland and Antarctica, is estimated to be in the range of $M = 127{,}000$–$217{,}000$ Gt, based on different studies [*Radić and Hock*, 2010; *Huss and Farinotti*, 2012; *Marzeion et al.*, 2012; *Grinsted*, 2013]. Glacier surfaces used to derive ice volume are provided by the Randolph Glacier Inventory [*Pfeffer et al.*, 2014]. The estimates correspond to about the year 2000. The rate of present glacier mass loss ($F = 240\ \mathrm{Gt\ yr^{-1}}$) refers to the period 2003–2009 [*Gardner et al.*, 2013].

The overall water volume of all lakes and rivers on Earth ($M = 178{,}000$ Gt) is based on a compilation by *Trenberth et al.* [2007]. Total annual runoff of all rivers on Earth into the ocean has been estimated by different authors based on river gauge observations, modeling, hybrid approaches, or the water balance [*Clark*

et al., 2015]. Average values for these approaches range from $F = 31{,}100$ to $F = 41{,}400$ Gt yr^{-1} [*Baumgartner and Reichel*, 1975; *Nijssen et al.*, 2001; *Fekete et al.*, 2002; *Clark et al.*, 2015]. Estimates of the total annual water withdrawal for irrigation range from $F = 2{,}200$ to $F = 3{,}800$ Gt yr^{-1}, mostly based on model-based approaches [e.g., *Oki and Kanae*, 2006; *Wisser et al.*, 2008; *Siebert et al.*, 2010; *Zhou et al.*, 2016]. Overall water withdrawals for domestic ($F = 380$ Gt yr^{-1}) and industrial ($F = 770$ Gt yr^{-1}) uses are based on *Oki and Kanae* [2006]. Total consumptive use of water by humans is estimated as $F = 1{,}380$ Gt yr^{-1} [*Flörke et al.*, 2013; *Zhou et al.*, 2016]. The total energy annually derived from hydropower production ($F = 10$ Exajoules yr^{-1}) is based on estimates made by *Goldemberg* [2000]. *Walling and Webb* [1996] estimated the cumulative annual sediment flux in all rivers globally as $F = 20$ Gt yr^{-1}, although the uncertainties in this estimate are large. Approximate global nutrient fluxes for nitrogen N ($F = 0.066$ Gt yr^{-1}) and for phosphorus P ($F = 0.011$ Gt yr^{-1}) are derived from a transport model by *Seitzinger et al.* [2005].

3. Past and Future Glacier Changes

Mountains accumulate snow, transform snow to firn and ice, and channel and regulate water runoff, which transports sediment and nutrients downstream. Glaciers, snow, and permafrost also store water in regions where other hydrological reservoirs, such as wetlands and aquifers, tend to be limited. A significant amount of water is currently stored in glacier ice in mid- to low-latitude mountain ranges, thus constituting a large hydrological reservoir in regions that shelter the majority of Earth's population (Table S1, Supporting Information). With a seasonal volume of around 9,000 Gt at the global scale (Figure 2), Earth's snow cover is an important element of the cryosphere that is linked to climate via a variety of feedback effects. *Brown and Mote* [2009] analyzed the impacts of climate change on the thickness and duration of snow cover in different mountain regions and found substantial effects on hydrology and ecosystems. In general, snow-to-rain ratios will decrease as air temperatures rise [*Knowles et al.*, 2006], and reductions in snow cover lead to positive feedbacks, enhancing the total radiative forcing of the Earth due to surface albedo changes [*Flanner et al.*, 2011].

Most mountain glaciers worldwide are strongly out of balance with climate and will lose up to one-third of their volume to achieve equilibrium state with current climate [*Mernild et al.*, 2013]. For the period 2003–2009, *Gardner et al.* [2013] estimated the mass loss of glaciers, excluding the ice sheets in Greenland and Antarctica, to be 240 Gt yr^{-1}, corresponding to an ocean water equivalent of 0.72 mm yr^{-1}, or about 30% of observed sea-level rise over this period. Despite the strong ice mass loss across all mountain ranges around the globe, a balanced mass budget has been reported for the early part of this century in some individual regions, for example the Karakoram [*Bolch et al.*, 2012; *Gardelle et al.*, 2012], which is likely due to changes in seasonality, atmospheric circulation, and enhanced winter snow accumulation on some glaciers [*Kapnick et al.*, 2014]. Projections using global circulation models (GCMs) for mountain ranges around the globe indicate major increases in air temperature over the next decades, but an inconsistent pattern for precipitation (Figures S1 and S2). Glacier models forced with GCM-output indicate continued ice loss in all regions [*Marzeion et al.*, 2012; *Giesen and Oerlemans*, 2013; *Radić et al.*, 2014; *Huss and Hock*, 2015]. By the end of the 21st century, relative losses in ice volume of between 30% (Alaska), around 50% (High Mountain Asia), and 80% (European Alps and low latitudes of the South American Andes) are expected, with considerable agreement among different models (Table 1). The total contribution to sea-level rise from mountain glaciers is estimated to be 90–220 mm by 2100 depending on the GCM and the emission scenario considered [*Marzeion et al.*, 2012; *Radić et al.*, 2014; *Huss and Hock*, 2015]. On time scales of a few centuries, an almost complete loss of mountain glaciers is possible if air temperatures continue to rise at current rates [*Levermann et al.*, 2013].

4. Assessing Changes in the Hydrology of Mountain Basins

Runoff from mountainous regions, except for those at low latitudes, is high during summer when other sources of water are often limited in the lowlands [*Barnett et al.*, 2005; *Viviroli et al.*, 2007]. Seasonal water releases from snow, ice, and permafrost are critical for maintaining hydrologic base flow, sediment and nutrient transport, and ecosystem structure and function, thereby providing vital environmental services and resources that are essential for human welfare both within mountains and much farther downstream [*Xu et al.*, 2009; *Immerzeel et al.*, 2010; *Viviroli et al.*, 2011].

Table 1. Calculated Relative Changes in Glacier Ice Volume Between About 2010 and 2100 for Selected Regions Based on Different Studies[a]

	Marzeion et al. [2012]	*Giesen and Oerlemans* [2013]	*Radić et al.* [2014]	*Huss and Hock* [2015]	Overall
Alaska	−28 ± 6%	−35 ± 10%	−25 ± 10%	−32 ± 11%	−30 ± 9%
Western Canada	−64 ± 7%	−45 ± 12%	−74 ± 9%	−76 ± 8%	−65 ± 9%
Scandinavia	−64 ± 10%	−28 ± 8%	−74 ± 24%	−81 ± 14%	−62 ± 14%
European Alps	−76 ± 11%	−88 ± 24%	−97 ± 13%	−77 ± 12%	−84 ± 15%
Caucasus	−53 ± 8%	−73 ± 20%	−75 ± 5%	−70 ± 11%	−68 ± 11%
Central Asia	−53 ± 8%	−54 ± 15%	−54 ± 15%	−54 ± 13%	−54 ± 13%
South Asia West	−39 ± 5%	−61 ± 17%	−41 ± 20%	−51 ± 11%	−48 ± 13%
South Asia East	−55 ± 7%	−88 ± 24%	−54 ± 15%	−66 ± 11%	−66 ± 14%
Sub-tropical Andes	−94 ± 7%	−66 ± 18%	−82 ± 5%	−79 ± 9%	−80 ± 10%

[a]The model results are based on the same emission scenario (Representative Concentration Pathway RCP4.5, except for *Giesen and Oerlemans* [2013], who use the A1B scenario) and the mean of 9–14 global circulation models. The results also are based on identical data on glacier area and distribution, but utilize different approaches to calculate glacier mass balance and retreat. Uncertainties refer to different global circulation models used to drive the glacier models.

To assess the present importance of the cryosphere for water availability in mountain catchments at low to mid-latitudes across all continents, we quantify the contributions of snow water equivalent (SWE) and effective rainfall (rain minus evapotranspiration) based on a combination of global remote-sensing data sets. This assessment is similar to the one made by *Kaser et al.* [2010], but relies on satellite-based observations of the relevant variables rather than climate re-analysis data. For the largest mountain catchments around the planet, we determine the annual totals of snow, glacier mass loss, rain, and evapotranspiration, allowing us to resolve the components of the water balance (Table 2). Data, methods, and uncertainties are described in detail in different studies [e.g., *Tedesco et al.*, 2004; *Bookhagen and Burbank*, 2010; *Bookhagen*, 2016] and are briefly summarized here.

4.1. Snow Water Equivalent (SWE)

Tedesco et al. [2004] provide daily grids of SWE (25 km resolution) based on microwave brightness temperatures using the AMSR-E/Aqua L3 product. Data are available continuously for the period 2002–2011 at the global scale. While there are considerable uncertainties in data derived from passive microwave monitoring at short temporal (i.e., daily) and spatial (at one to several pixels) scales, integration over seasons and entire catchments with drainage areas $>10^3$ km^2 is much more robust [*Smith and Bookhagen*, 2016]. Signal saturation at high snow depths might also affect the results [e.g., *Dong et al.*, 2005], but the effect of these uncertainties on our results at the basin-scale is considered to be limited.

4.2. Rainfall (R)

To estimate the distribution of annual rainfall (liquid precipitation) across all analyzed catchments, we use the Tropical Rainfall Measuring Mission (TRMM) 3B43V7 data set [*Huffman et al.*, 2007]. This data set provides precipitation estimates from multiple satellites, as well as gauge analyses for the period 1998–2012 at a spatial resolution of about 25 km × 25 km (0.25° × 0.25°). TRMM 3B43V7 overestimates single-event rainfall in mountain catchments [e.g., *Bookhagen and Burbank*, 2010; *Wulf et al.*, 2016], but provides reasonable estimates on larger spatial and longer temporal scales [e.g., *Carvalho et al.*, 2012; *Boers et al.*, 2015]. Although the TRMM 3B43V7 data set has been adjusted using precipitation gauges [*Huffman et al.*, 2007], its performance in remote high mountain environments remains difficult to assess because of limited availability of high-quality, long-term rain gauges in these areas.

4.3. Evapotranspiration (ET)

Data on effective evapotranspiration are provided by the MOD16 product [*Mu et al.*, 2007], which is derived from MODIS data at monthly to annual intervals with a spatial resolution of 1 km. The data set spans the

Table 2. Cryospheric, Hydrologic, and Demographic Characteristics of the Major Mountain Basins Analyzed in Figure 3[a]

River Catchment Unit	Basin Area (10^3 km^2)	Population Density (p. km^{-2})	Ice Volume (10^9 m^3)	Glacier Cover (%)	SWE + ΔM_g (10^9 m^3 yr^{-1})	R−ET (10^9 m^3 yr^{-1})	C (%)
Asia							
Yangtze	1,913	248	201	0.14	110	1,265	8
Tarim[(e)]	1,218	9	2,413	2.25	406	131	76
Junggar Basin[(e)]	1,038	11	125	0.28	364	144	72
Tibetan Plateau[(e)]	1,011	1	760	0.85	413	66	86
Ganges	948	399	793	1.30	81	797	9
Indus	859	175	2,559	3.13	262	313	46
Yellow	803	146	11	0.02	61	143	30
Mekong	773	67	29	0.06	29	699	4
Amudarya[(e)]	623	35	1,146	2.38	180	214	46
Brahmaputra	533	109	1,053	3.43	138	594	19
Lake Balkash[(e)]	415	12	157	0.68	189	95	67
Syrdarya[(e)]	326	61	60	0.38	113	92	55
Salween	265	26	62	0.48	47	124	28
Total	10,727	124	9,369	1.03	2,393	4,678	34
South America							
Amazon	5,888	4	62	0.03	4	8,050	0
Orinoco	934	11	0	0.00	0	1,639	0
Altiplano[(e)]	356	7	22	0.18	71	62	53
Central Andes	322	29	49	0.44	12	23	34
Magdalena	259	109	1	0.01	0	403	0
Total	7,760	11	135	0.05	86	10,178	1
North America							
Columbia	653	10	110	0.31	123	284	30
Colorado	628	12	0	0.00	76	86	47
Fraser	232	5	147	1.10	73	194	27
Total	1,513	14	257	0.28	272	564	33
Europe							
Danube	791	103	15	0.04	54	578	9
Rhine	164	298	19	0.21	11	97	10
Rhone	97	99	57	0.89	14	111	11
Po	73	221	16	0.45	18	79	18
Total	1,124	140	107	0.18	97	865	10

[a]Endorheic basins are marked with superscript (e). Population densities for 2000 are based on *Center for International Earth Science Information Network (CIESIN) et al.* [2005]. Snow water equivalent (SWE), glacier mass change (ΔM_g) total annual rainfall (R) and evapotranspiration (ET) are derived from remote sensing data, and the overall relative melt contribution C is calculated using equation (1).

period 2000–2010 and provides reasonable estimates for mountainous regions, for example, the Himalayas [*Bookhagen and Burbank*, 2010; *Wulf et al.*, 2016] and Tibet [*Chen et al.*, 2014]. We note that evapotranspiration is low in vegetation-free, high-elevation regions.

4.4. Glacier Mass Change (ΔM_g)

Annual glacier mass changes for large mountain regions (High Mountain Asia, European Alps, South American Andes, Coast and Rocky Mountains of North America) for the period 2003–2009 have been documented by *Gardner et al.* [2013] based on a combination of different remote sensing and in situ data sets. We have linearly distributed these mass changes over all individual catchments, assuming each glacier will exhibit the same rate of annual thinning as the mountain-range mean. Note that the sum of water issuing from glacier surfaces derives from glacier mass change, snow melt, and rain.

4.5. Contribution of Snow and Ice Melt to Runoff (C)

Combining the above data sets, we quantify to a first order the annual contribution of snow and ice (i.e., melt of the seasonal snow and annual glacier mass loss) to catchment runoff, defined as the sum of effective rainfall (R−ET) and runoff from seasonal snow and ice melt (SWE + ΔM_g). The relative contribution of the cryosphere to runoff is calculated as:

$$C = \left(\mathrm{SWE} + \Delta M_g\right) / \left(\mathrm{R} - \mathrm{ET} + \mathrm{SWE} + \Delta M_g\right) \tag{1}$$

We assume that all discharge is derived from the four components (SWE, ΔM_g, R, ET).

For the present analysis, we assume that the differences in the time periods covered by the individual data sets are negligible. The assessment is thought to be representative for the first decade of the 21st century. Our analysis does not account for groundwater retrieval [*Andermann et al.*, 2012; *Bookhagen*, 2012] and irrigation, which could cause water losses over large parts of the downstream basins.

Our data indicate that present glacier ice volume at low to mid-latitudes is concentrated in High Mountain Asia with smaller volumes in the European Alps, the Caucasus, the Coast and Rocky Mountains, and the Andes (Figure 3a, Table 2). Our simple method for estimating the cryospheric contribution to runoff in mountain catchments (equation (1)) indicates the importance of melting processes, and hence increased potential impacts of future climate change, in rather dry high-elevation regions. We find snow and ice melt contributions of 50% and more in some large-scale basins of High Mountain Asia, as well as in the Andes

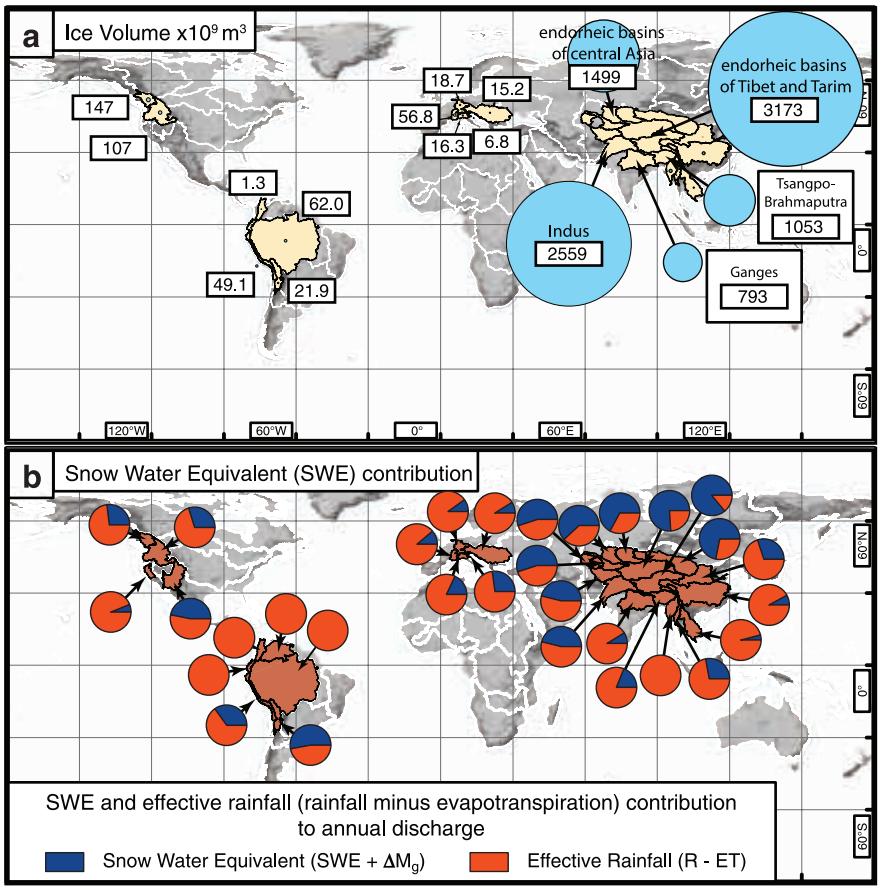

Figure 3. Hydrologic parameters of large mountain catchments. (a) Present-day glacier ice volume within large watersheds in mid- to low-latitude mountain ranges. Blue circles are scaled to ice volume. (b) Relative contributions of snow water equivalent and effective rainfall to total basin runoff. See Table 2 for more detailed information.

(Figure 3b, Table 2). These regions support large populations and also have experienced large population growth over the past decade (e.g., Indus, Table S1). Cryospheric contributions in regions influenced by monsoonal systems are generally small or negligible (e.g., Brahmaputra, Amazonas; Table 2). We note that across most basins the contribution from annual glacier mass loss (ΔM_g) is relatively small (mostly between 0.5% and 5%) compared to the melting of seasonal snow (SWE) (Table S2). However, annual glacier mass loss incompletely describes glacier contributions to runoff because the seasonal hydrological effect of glaciers is dominant [*Radić and Hock*, 2014]. These findings are consistent with earlier studies [e.g., *Schaner et al.*, 2012].

The importance of changes in snow and ice to downstream regions is determined by the hydrological regime of meltwater-fed streams (Figure 3b), ecological systems, and water demand, the last of which is dictated by population density and the importance of runoff to energy, agriculture, and other water-intensive sectors (Tables S1 and S2). Physical understanding and modeling suggest that changes in the type and temporal scale of runoff from glaciers depend on factors such as glacier size, elevation range, and hypsometry, the proportion of glacier cover in a catchment, and the way the glacier melt signal convolves downstream with other hydrological signals (i.e., groundwater, precipitation, and evapotranspiration). In some basins characterized by an arid summer climate, glacier meltwater accounts for up to 50% of melt season discharge [*Kaser et al.*, 2010; *Huss*, 2011; *Schaner et al.*, 2012; *Sorg et al.*, 2012]. Runoff from larger glaciers may increase for a few years to decades during the initial period of negative glacier mass balance, but will inevitably be followed by a decrease in the longer term [*Milner et al.*, 2009; *Mark et al.*, 2015]. Recent studies show that some watersheds with small glaciers in the Andes, North America, and Europe have already reached their "tipping points", also termed "peak water", and show decreasing annual discharge [*Baraer et al.*, 2012; *Frans et al.*, 2016]. Some local and regional-scale modeling studies confirm that runoff from glacierized catchments may increase for a few more decades, albeit with shifts in seasonal regimes [*Farinotti et al.*, 2012; *Immerzeel et al.*, 2013; *Bliss et al.*, 2014; *Lutz et al.*, 2014; *Ragettli et al.*, 2016]. However, a more comprehensive perspective across all glacierized regions of the world is still missing.

4.6. Future Changes in Mountain Hydrology

To investigate future changes in runoff from Earth's glaciers, we rely on model results from the Global Glacier Evolution Model (GloGEM) [*Huss and Hock*, 2015]. The model calculates distributed surface mass balance and glacier geometry changes in response to climatic forcing for each of the roughly 200,000 glaciers on the planet. GloGEM is forced with downscaled monthly air temperature and precipitation provided by 14 GCMs from the Climate Model Intercomparison Project CMIP5 [*Taylor et al.*, 2012]. The glacier model is calibrated using observed glacier mass changes [*Gardner et al.*, 2013] and is validated against in situ data from the World Glacier Monitoring Service [*World Glacier Monitoring Service (WGMS)*, 2012]. Initial ice thickness distribution is updated in annual time steps according to calculated surface mass balance (accumulation plus refreezing minus snow/ice melt). For each of the world's glaciers, GloGEM calculates the altitudinal distribution of surface mass balance at a vertical resolution of 10 m. This also allows the glacier's equilibrium line altitude to be derived now and in future (Figure 4).

Based on GloGEM, we calculate runoff from all presently glacierized surfaces within a drainage basin as the sum of snow/ice melt plus rain minus refreezing (i.e., all water exiting the glacier snout) [see *Radić and Hock*, 2014]. To ensure comparability of runoff volumes over time, we keep the catchment area over which future glacier runoff is evaluated constant during glacier retreat, even if the modeled ice area only covers part of the original basin toward the end of the century. We thus term calculated future runoff stemming from surfaces that are glacierized today as "headwater runoff" (Figure 4).

Figure 4 reveals important differences in the characteristics of glacierized watersheds around the world. Their area-elevation distribution defines ice cover and hence the response times of glaciers and potential future volume losses. In general, we find that headwater runoff continues to increase in the future in catchments with large ice volumes such as in northern North America, parts of the Himalayas, and Central Asia. In contrast, regions with smaller ice volumes at present such the Alps in Europe and the tropical Andes, face a decrease in runoff compared to current conditions. Our results are consistent with earlier findings on the importance of glacier meltwater to runoff [e.g., *Kaser et al.*, 2010; *Schaner et al.*, 2012], but extend the perspective globally and into the future and underline the importance of differences among individual basins. For instance, the contrast between individual basins is particularly strong in High Mountain Asia where the glacier melt season in the densely populated Indus, Ganges, and Brahmaputra basins coincides

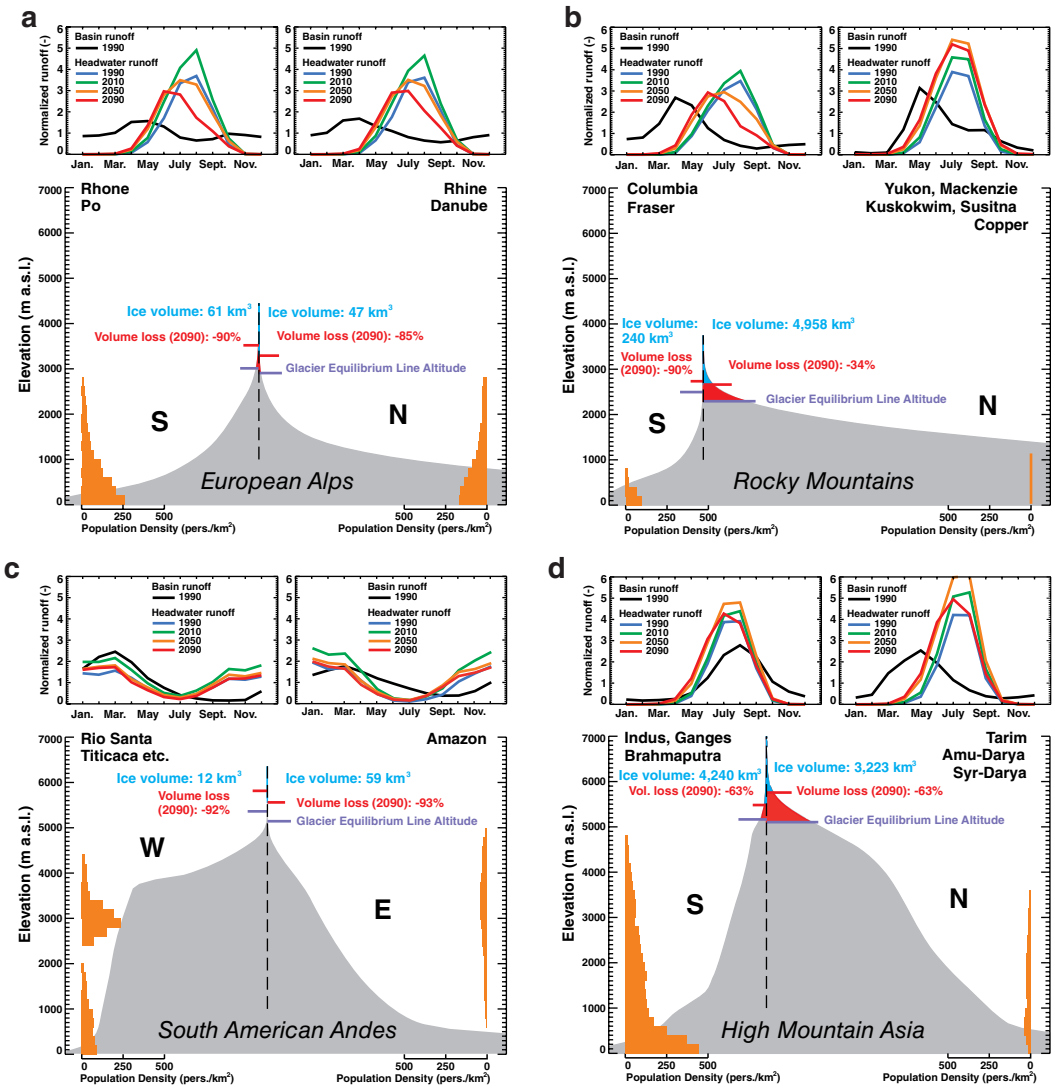

Figure 4. Cumulative land surface hypsometry [*Farr et al.*, 2007] of the world's major glacierized drainage basins: (a) European Alps, (b) western North America, (c) South America, and (d) High Mountain Asia, separated by the main weather divide (e.g., North/South). Present glacier ice volume and basin-averaged glacier equilibrium lines are shown as purple horizontal lines. The present-day (1980–2000) average equilibrium line altitude is based on a glacier area weighted mean. Also shown are modeled future changes in glacier volume and potential loss of glacier area (red), and reductions in equilibrium line altitude (red horizontal lines). Current population density as a function of elevation for each catchment indicates that people living in the lowlands depend on mountain water. Insets show both the observed runoff regime (period 1986–1995) of the respective basins (total monthly discharge normalized with average annual runoff), as well as present-day and future modeled runoff from glacierized areas based on *Huss and Hock* [2015]. Future changes in runoff due to a reduction in snow cover outside glaciers are not included in this analysis.

with high river runoff in the monsoon season, leading to small melt-to-discharge ratios (Figures 3b and 4, Table S2), whereas Central Asian watersheds are characterized by a summer-dry climate and streamflow is substantially enhanced by glacier melt in July and August.

Our global-scale assessment shows the major shifts in seasonal runoff regimes around the world that will result from the effect of reduced snow cover and ice. The results highlight the need to distinguish between the responses of individual basins following a transition toward mountains without permanent snow and ice. Seasonal shifts will be especially important in mid-latitude regions with moderate glacier volumes such as the European Alps and the mountains of western North America and accordingly will have substantial impacts on the hydropower sector, which is important in these regions. Water resource management will also be challenged in regions where glacier melt water is particularly important, notably seasonally dry regions such as parts of the tropical Andes and Central Asia (Figure 4). In addition, the decrease in snow

and ice will likely increase the "flashiness" of mountain streams [*Tang et al.*, 2014]. Runoff will respond more rapidly to rainfall as glacier areas decrease, snow-to-rain ratios tend to become smaller, and the zero-degree line rises [*Knowles et al.*, 2006]. Runoff extremes are likely to occur more frequently in the coming decades, as are long-lasting droughts [*Collins et al.*, 2013]. It is important to note that these hydrological changes will become general in mountain regions, as climate models largely agree that temperature will increase worldwide (Figure S1).

5. Sediment Flux and Hazards in Mountain Areas

Erosion and sediment mobilization, transport, and deposition are fundamental processes in high-mountain regions, with potentially large impacts on society. Here, we review recent progress in understanding the physical processes and related impacts for a future without permanent snow and ice.

Sediment production rates from bedrock, normalized to unit area, are highest in the world's mountains [*Hallet et al.*, 1996]. Much research has been completed on erosion rates in glacierized catchments and on the interplay of climate, glaciers, topography, and tectonics [e.g., *Thomson et al.*, 2010; *Herman et al.*, 2013]. Glacial erosion rates are typically estimated from sediment yield data acquired from rivers and lakes, and range over four orders of magnitude around the world, from <0.1 mm yr^{-1} to about 100 mm yr^{-1} [*Hallet et al.*, 1996; *Koppes and Montgomery*, 2009]. Recently, progress has been made in quantitatively linking glacial erosion rates to glacier sliding velocity [*Herman et al.*, 2015] and to ambient temperature, precipitation, and thus glacier thermal regime [*Koppes et al.*, 2015]. However, there is still limited understanding of the effects of glacier recession on erosion and sediment production. Major gaps in understanding include: (i) the effects of changes in the cryosphere on sediment production on decadal and centennial time scales, as opposed to longer ones and (ii) a comprehensive system perspective that considers the full cryosphere and geomorphic systems. Recent studies that adopt a landscape approach emphasize the importance of the connectivity of different areas within a catchment to decadal-scale changes in sediment production and delivery in attempts to quantify the catchment-scale response to glacier recession [*Lane et al.*, 2016]. Case studies from a large glacierized catchment in the Alps (Monte Rosa, Italy) highlighted that slope instabilities linked to air temperature changes, glacier recession, and permafrost thaw in the late 20th century and the first decade of the 21st century caused an increase in the catchment-scale erosion from 1–2 mm yr^{-1} to about 50 mm yr^{-1} [*Fischer et al.*, 2013]. Important progress has been made in documenting the relations between alpine permafrost degradation and slope destabilization [*Krautblatter et al.*, 2013], but still little is known about their related effects on sediment production and flux at the catchment scale. Anecdotal evidence suggests that cryospheric changes in recent years may be driving geomorphic systems to tipping points, resulting in completely altered mass movement regimes with tremendous impacts on mountain communities, critical energy and transport lines, and hydropower infrastructure [*Huggel et al.*, 2012].

Extreme precipitation and runoff events play an important role in sediment mobilization and transport. High-intensity precipitation, rain-on-snow events, and outburst floods from glacier-, moraine-, and landslide-dammed lakes generate some of the largest hydrologic and sediment-transport events on Earth, with volumes of up to 10^7–10^8 m^3 of sediment delivered in single events and with significant impacts more than 100 km downstream [*Richardson and Reynolds*, 2000; *Korup and Tweed*, 2007]. Glacier lake outburst floods may become more frequent as glaciers thin and recede because new lakes will form and existing ones might grow. Many glacier-dammed lakes will be impacted by mass movements from adjacent destabilized mountain slopes [*Dussaillant et al.*, 2009; *Haeberli et al.*, 2016]. Global and regional climate models indicate that the frequency and intensity of future heavy precipitation events will scale with the rise in global mean temperature and cumulative total greenhouse gas emissions [*Seneviratne et al.*, 2016]. As indicated in the previous section, the synergistic effects of a higher frequency of extreme weather events and a reduced cover of snow and ice to dampen runoff peaks will result in a higher frequency of runoff extremes and thus likely produce higher sediment transport rates and associated impacts on downstream ecosystems and populations. Specifically, there will be substantial effects of enhanced sediment transport and deposition on water quality, aquatic habitat, flooding, infilling of hydropower reservoirs, turbine abrasion, and agricultural and infrastructural development [*Schaefli et al.*, 2007; *Finer and Jenkins*, 2012]. Hydropower infrastructure, especially in headwater regions of the Himalayas, Andes, and Alps, is particularly at risk from increased sediment flux and extreme hydro-geomorphic events [*Schaefli et al.*, 2007; *Wulf et al.*, 2010; *Finer and Jenkins*, 2012].

The magnitude of these impacts is site- and catchment-specific and depends on the resilience and buffering capacities of the system, including the area occupied by glaciers and permafrost, basin hypsometry, groundwater systems, vegetation type and cover, and ecosystem types [*Bruijnzeel et al.*, 2011; *Buytaert et al.*, 2011; *Andermann et al.*, 2012]. The population and infrastructure within the catchment then determine vulnerability and potential damage. However, even within the best-monitored high-mountain catchments, there is still only a rudimentary quantitative understanding of hydro-geomorphic processes and their relation to climate change over relevant spatial and temporal scales. Yet, there is sufficient understanding and evidence to suggest that sediment processes need to be more strongly considered in water resource research and management in deglaciating mountain regions.

6. Aquatic and Terrestrial Ecology

A few organisms, mainly algae and microbes, live in snow and ice [*Anesio and Laybourn-Parry*, 2012]. Many more rely indirectly on the presence of snow and ice, and on their melt. Consequently, aquatic and terrestrial biological communities and processes in mountains are profoundly affected by climatic change, both related and unrelated to changes in the cryosphere.

Numerous studies have demonstrated upward shifts of species and communities in mountains [*Lenoir et al.*, 2008; *Chen et al.*, 2011; *Telwala et al.*, 2013]. Data from the extensive network of monitoring sites covered by the GLobal Observation Research Initiative in Alpine environments (GLORIA) have revealed an increase in the abundance of thermophilic (warm-adapted) plant species at high elevations and an upward shift of 2.5–2.7 m in the distribution limits of species from 2001 to 2008 [*Gottfried et al.*, 2012; *Pauli et al.*, 2012]. In the same period, mean species richness increased by a factor of 3.9 on boreal-temperate mountains, while it decreased by 1.4 on Mediterranean mountains, probably due to climatically driven reduced water availability in Southern Europe [*Gottfried et al.*, 2012; *Pauli et al.*, 2012]. A meta-analysis of worldwide treeline data shows that in 52% of sites, the treeline has been advancing uphill while only 1% reported treeline recession [*Harsch et al.*, 2009]. Warming conditions and advancing plant communities are reducing high alpine habitats and thus space for specialized high alpine species [*La Sorte and Jetz*, 2010; *Dirnbörk et al.*, 2011]. However, climate-mediated range shifts are not necessarily related to changes in the cryosphere as such; they also happen in areas without glaciers. Studies of the ecological effects of the retreating cryosphere are still relatively few, so our understanding of these effects is far from complete and remains largely qualitative. Some trends, however, are well documented and unequivocal.

Rising air temperatures and the attendant shorter duration of snow cover directly influence the length of the growing season and the phenology of plant production and consumers, and thus the alpine-treeline ecotone [*Gottfried et al.*, 2012]. Higher temperatures also increase above-ground net primary production as long as there is no decrease in soil moisture that mediates soil nitrogen availability [*Berdanier and Klein*, 2011]. However, decreasing snow cover and an earlier growing season also expose wildflowers to frost damage [*Inouye*, 2008]. Early snowmelt decreases the mortality rates of some conifers such as *Pinus cembra*, whereas winter and summer drought reduce growth [*Oberhuber*, 2004]. Earlier loss of snowpack and more summer drought are already affecting tree species such as *Pinus contorta*, and at the same time increasing the risk of infestations by bark beetles [*Coops et al.*, 2010].

Receding glaciers and declining snow cover create new habitats and space that is colonized by early-succession, scree slope, and perennial clonal plants [*Chapin et al.*, 1994; *Cannone et al.*, 2008]. The presence of some keystone plants will be crucial for limiting soil erosion on steep slopes. However, some of these species (e.g., *Festuca valesiaca* in the Caucasus) already cope with dry conditions at their physiological limits [*Caprez et al.*, 2011], and increasing drought might limit the ability of such species to sustain this key ecosystem function [*Loreau et al.*, 2002]. Lack of water also inhibits soil microbial activity, thereby decreasing nutrient availability [*Stark and Firestone*, 1995] and primary production. Changes in the amount and seasonal availability of resources for consumers can potentially lead to mismatches, with cascading effects on food webs [*Miller-Rushing et al.*, 2010]. Initial increases in meltwater may elevate phosphorus and nitrogen inputs to downstream alpine wetlands and floodplains during high flows, enhancing the productivity of terrestrial communities [*Tockner et al.*, 2002].

The mountain cryosphere influences downstream aquatic ecosystems by governing flow regimes, channel stability, sediment concentration, water temperature, and nutrient supply, and is essential for supporting

life during dry periods when snow and ice melt is the main water source. Due to harsh environmental conditions, macroinvertebrate communities in glacier-fed rivers are deterministic and dominated by a few specialized cold-water species close to the glacier [*Milner et al.*, 2001] where they find refuge from competitors [*Lencioni et al.*, 2015]. An increase in glacier meltwater runoff will lead to a colder and harsher aquatic environment, and possibly a downstream displacement of aquatic communities [*Jacobsen et al.*, 2014]. In the long term, however, glacier retreat will result in increases in stream temperatures in meltwater streams; sites that were next to the snout of Swiss glaciers in 1998 were 160–480 m farther away in 2009, and had a 2–4°C higher mean summer stream temperature [*Robinson et al.*, 2014]. The mean August temperature of an Alaskan stream increased from 2 to 18°C during from 1978 to 2003 as a result of the complete disappearance of its feeding glacier [*Brown and Milner*, 2012]. Such streams are quite quickly colonized by aquatic communities adapted to higher water temperatures [*Finn et al.*, 2010; *Robinson et al.*, 2014]; specific sites experience increasing species richness through time, tracking rising water temperature and other changing environmental conditions [*Milner et al.*, 2011].

Few datasets allow direct study of the long-term effects of glacier retreat on ecology in mountain streams [*Finn et al.*, 2010; *Milner et al.*, 2011]. However, "space-for-time" substitutions, a commonly used approach in ecology in which sites covering a gradient in glacier cover are used to predict effects of glacial retreat, point to similar results (Figure 5). They show that the richness of local aquatic macrofauna (alpha diversity) peaks at intermediate levels of glacial runoff [*Jacobsen et al.*, 2012; *Khamis et al.*, 2016]. Furthermore, the reduction and eventual loss of meltwater flow is predicted to: (i) reduce environmental heterogeneity at the watershed level, reducing species turnover among sites (beta diversity) [*Jacobsen et al.*, 2012; *Cauvy-Fraunié et al.*, 2015]; (ii) cause the loss of rare and specialized species from the regional species pool (gamma diversity) [*Jacobsen et al.*, 2012; *Quenta et al.*, 2016]; and (iii) elevated algal and herbivore biomasses, thus shifting ecological structure [*Cauvy-Fraunié et al.*, 2016]. In addition, genetic diversity within individual species decreases in headwater areas as glacier melt diminishes, because with less isolation individuals intermix to a greater degree when mating [*Finn et al.*, 2013]. Reduced meltwater also has been shown to reduce migratory corridors for anadromous fish [*Milner et al.*, 2009]. Finally, a shorter duration of snow cover shifts life cycles. For example, earlier emergence [*Finn and Poff*, 2008] and increased production of stream insects [*Schütz et al.*, 2001] may benefit terrestrial invertebrates, reptiles, and birds.

An earlier onset of melting of lake surface ice will affect the heat content, underwater light climate, temperature regime, oxygen regime, and mixing of lakes [*Melack et al.*, 1997]. Indirectly, changes in melting in the catchment can affect downstream lakes through changes in water level, turbidity, water chemistry,

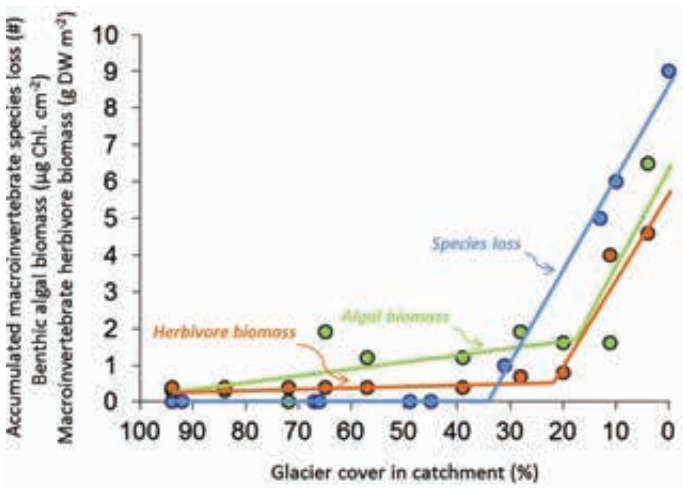

Figure 5. Ecological features of small streams with different percentages of glacier cover in a watershed draining Antisana volcano in the Ecuadorian Andes. *Accumulated species loss* is the number of macroinvertebrate species with a preference for streams influenced by glacier meltwater that are lost from the regional species pool at sites with declining glacier cover. *Algal biomass* is the amount in chlorophyll units (µg cm^{-2}) of algae (periphyton) in stream channels. *Herbivore biomass* is the amount in g dry-weight m^{-2} of the functional feeding group of macroinvertebrates that primarily live on the algae. Data from *Jacobsen et al.* [2012] and *Cauvy-Fraunié et al.* [2016].

input of nutrients and other solutes, and the timing of this input. These changes will individually and synergistically strongly affect benthic and pelagic communities [*Parker et al.*, 2008; *Slemmons et al.*, 2013]. For example, suspended sediment loads from glacier meltwater increase turbidity, which protects zooplankton from ultraviolet B radiation, but also limits light penetration for phytoplankton production and obstructs feeding by zooplankton [*Sommaruga*, 2015]. Due to glacier retreat, proglacial lakes are currently forming at a high rate in most arctic and alpine areas of the world [*Carrivick and Tweed*, 2013]. Typically, these lakes are initially dominated by microbes and devoid of higher life [*Sommaruga and Kandolf*, 2014]. Later, they are colonized by algae, protozoans, and invertebrates, and food webs form [*Sommaruga*, 2015]. As glaciers disappear, or lakes lose connection to them, lake transparency increases, affecting the fitness of species with high demands for phosphorus and increasing ultra-violet radiation and visual predation pressure [*Balseiro et al.*, 2008; *Laspoumaderes et al.*, 2013].

7. Societal Adaptation and Management Strategies

The current transient state of climate, together with future greenhouse gas emissions, will ensure an irreversible loss of glaciers, permafrost, and permanent snow in some mountain ranges, irrespective of future mitigation undertaken by society to moderate climate change. Adaptation to the loss of snow and ice will thus be required in all mountain regions [*Field et al.*, 2012]. Yet, physical, ecological, and socio-economic systems in mountains are multi-faceted, and behave and respond in ways that differ considerably across mountain watersheds [*Das et al.*, 2011]. These systems are typically more complex than can be fully captured by historic observations or simple predictive models. This complexity poses major challenges to adaptation [*Buytaert et al.*, 2010]. On the other hand, general trends in the response of some sub-systems (e.g., the water cycle) to rising air temperatures are relatively well understood, allowing strategies to be developed for the future. A region's sustainability will depend on the capacity to cope with the challenges of climate change, and this will be affected by multiple factors such as the prevailing governance structure, the ecological integrity of the region, and justice accessing local resources [*Schneider et al.*, 2015]. Society should focus on an adaptive governance approach, with continuous learning and flexibility as key aims [*Folke et al.*, 2005]. Information about how systems respond to environmental and human stressors, and the ability to adapt by changing direction are of first-order importance [*Pahl-Wostl*, 2009].

In specific catchments of the European Alps, for example, unprecedented mass wasting related to permafrost degradation has strongly elevated sediment fluxes, requiring a re-evaluation of transport routes and relocation of mountain communities under economic, touristic, energy, and social pressures [*Huggel et al.*, 2012]. In the Andes of Peru, rock and ice avalanches from steep slopes have impacted lakes that formed as glaciers receded, triggering localized disastrous downstream floods and debris flows. At the same time, shrinking glaciers change water availability for local and regional economies during the dry season [*Bury et al.*, 2013]. Emerging adaptation efforts should therefore be focused on water retention measures that address water availability issues and reduce the risk of outburst floods. Nevertheless, actual water usage patterns are more profoundly impacted by societal forces than climatically mediated hydrological supply, underscoring the need to adopt a socio-hydrologic framework to evaluate legal, economic, political, cultural, and social drivers [*Carey et al.*, 2014].

Multiple-use water storage and distribution strategies, for example, systems that meet both irrigation and drinking water needs, will play a key role in future water resource management and in helping communities offset for decreasing storage of water in snow and ice with associated disruptions in the seasonality of flow. Traditionally, water storage infrastructure has been built for single uses (e.g., hydropower, flood control, or irrigation), but changes in seasonal supply and demand will require management for multiple uses. This reassessment requires consideration of the socio-political context with considerable lead-time [*Clarvis et al.*, 2014; *Schneider et al.*, 2015]. Given the importance of temporal and spatial scaling issues and system complexity, the most effective strategies will emerge from regional planning, knowledge sharing, and compromises among the competing water needs of multiple users as well as ecosystem needs. Furthermore, in less developed regions, capacity building, training, and international cooperation continue to be important, and corresponding international environmental policies need to be strengthened.

Limitations to our understanding of mountain environments, as well as the challenges of adaptive management, have implications for future research priorities. There is a compelling need to improve our

understanding of environmental and ecological systems in mountain regions. We have only a limited quantitative comprehension of these systems and their interactions. A stronger knowledge base can better inform sustainable decision-making, which requires a system approach grounded in understanding interactions, impact cascades, and thresholds in the physical and ecological environments. We thus recommend concerted and collaborative efforts to acquire multidisciplinary observations in representative catchments of distinct regions. Ideally, these should be guided by common protocols, similar to the GLORIA network [*Grabherr et al.*, 2000; *Pauli et al.*, 2005; www.gloria.ac.at]. Furthermore, we advocate research programs that involve the full spectrum of stakeholders in order to take into account local experience and views about possible future developments [e.g., *Valdivia et al.*, 2010]. Creating a relevant base of evidence for adaptive governance should foster development of distinct geographic solutions and approaches that may differ among regions because of different social, cultural, and economic interests. A key issue for inhabitants of mountains experiencing climate and other stresses is their resilience in the face of constantly changing conditions and their ability to adapt and maintain basic functions and services [*Folke et al.*, 2010].

Based on our analysis, which has involved both qualitative and quantitative assessments of the directions of change in the mountain cryosphere, it is clear that many important questions remain, requiring more extensive research on specific aspects of the physical, biological, and socio-economic environments of mountain regions. We also recognize major challenges that transcend traditional disciplinary science, requiring further research at the science-society interface.

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Earth's Future

Supporting Information for

Disappearing World Heritage glaciers as a keystone of nature conservation in a changing climate

J. Bosson[1], M. Huss[2,3] and E. Osipova[1]

[1]World Heritage Programme, International Union for Conservation of Nature (IUCN), Gland, Switzerland.

[2]Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland.

[3]Department of Geosciences, University of Fribourg, Fribourg, Switzerland.

Contents of this file

Figures S1 to S4
Tables S3

Introduction

This supporting information provides additional figures and tables complementing the main text. The additional tables S1, S2, S4 and S5 are uploaded in another file because the have A3 format.

Figure S1. Example of World Heritage glaciers mapping in the region of Los Glaciares National Park (South Patagonia). Glaciers outlines originate from RGIv6.0 (RGI Consortium, 2017). Background source: Microsoft® Bing™ Maps.

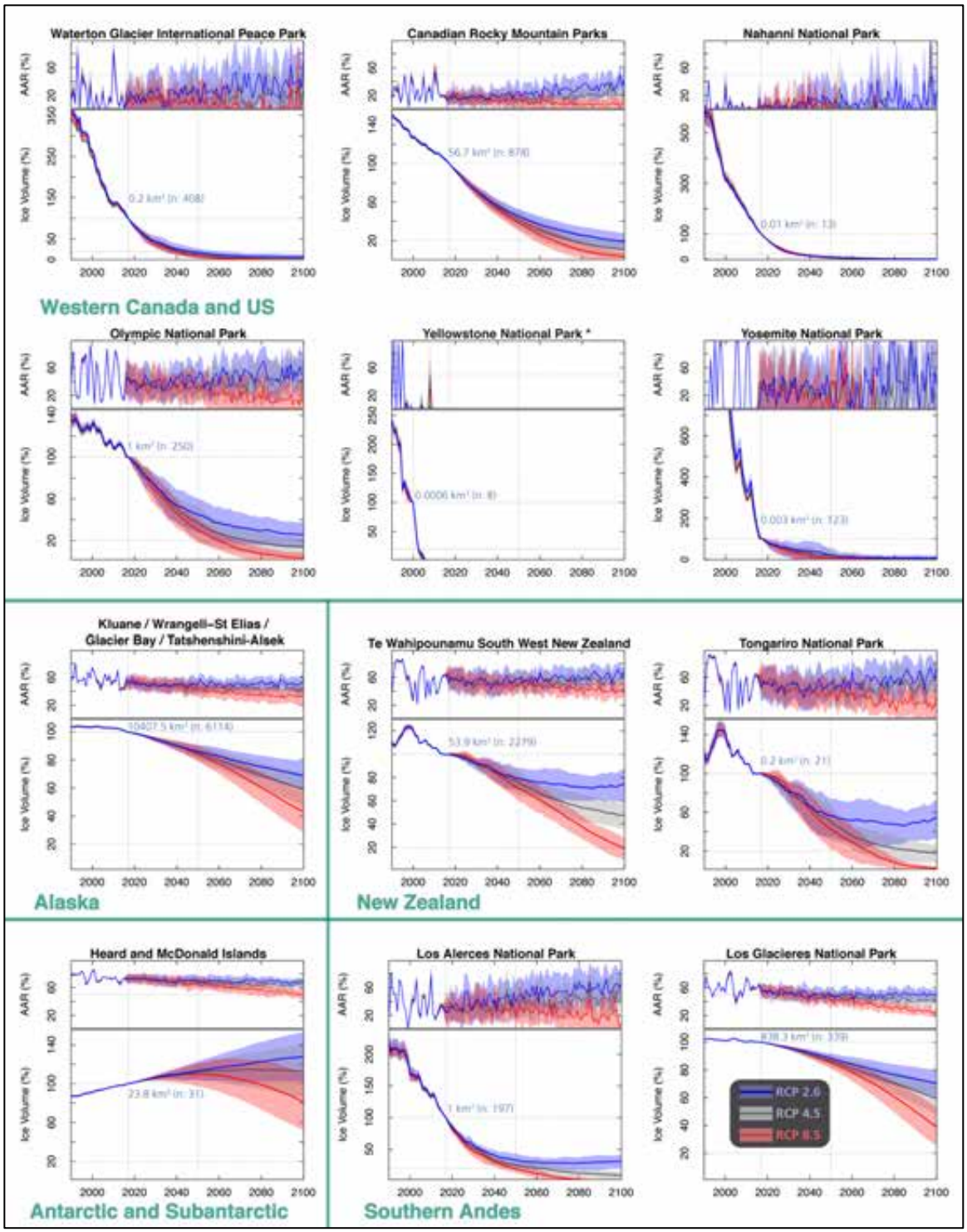
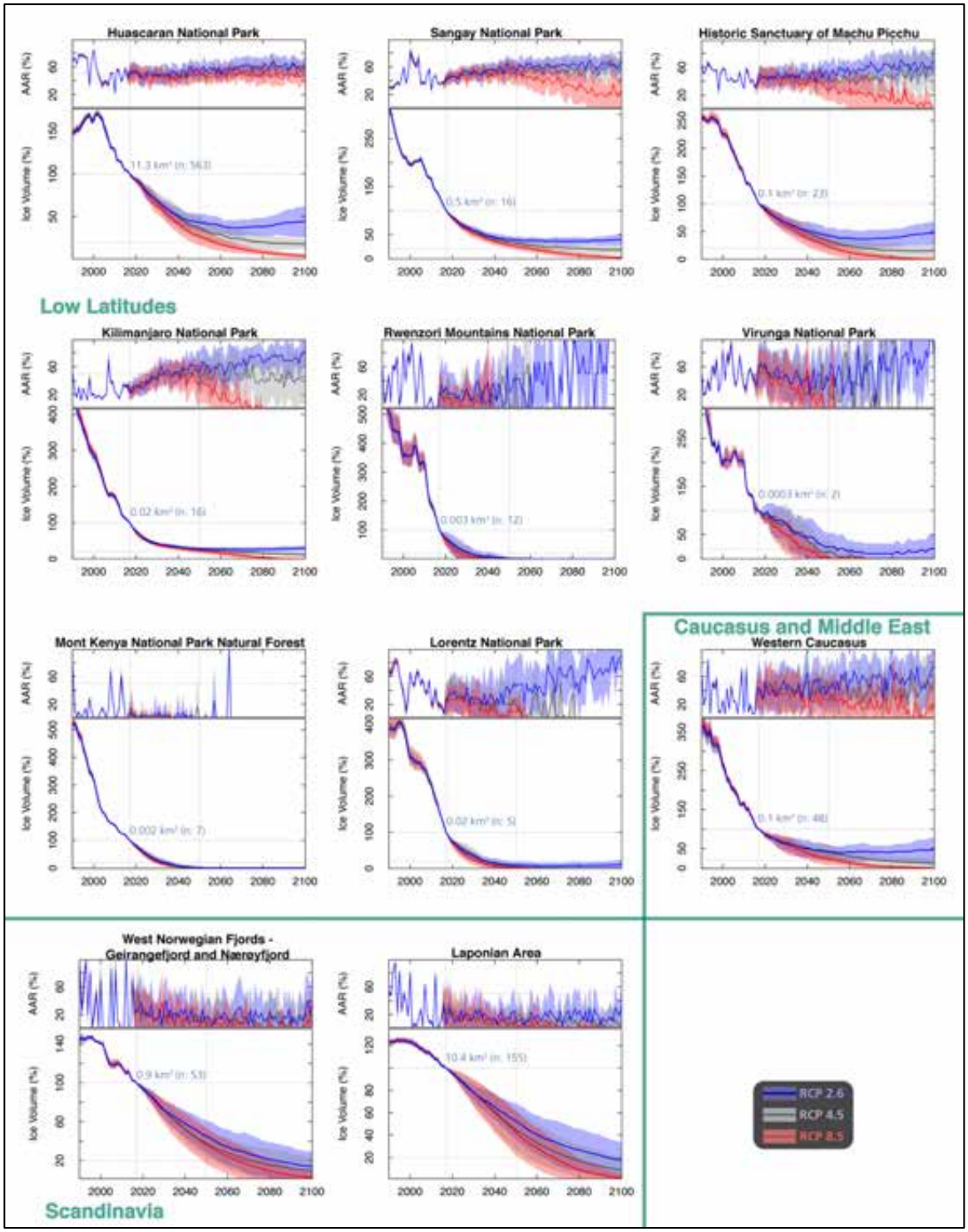
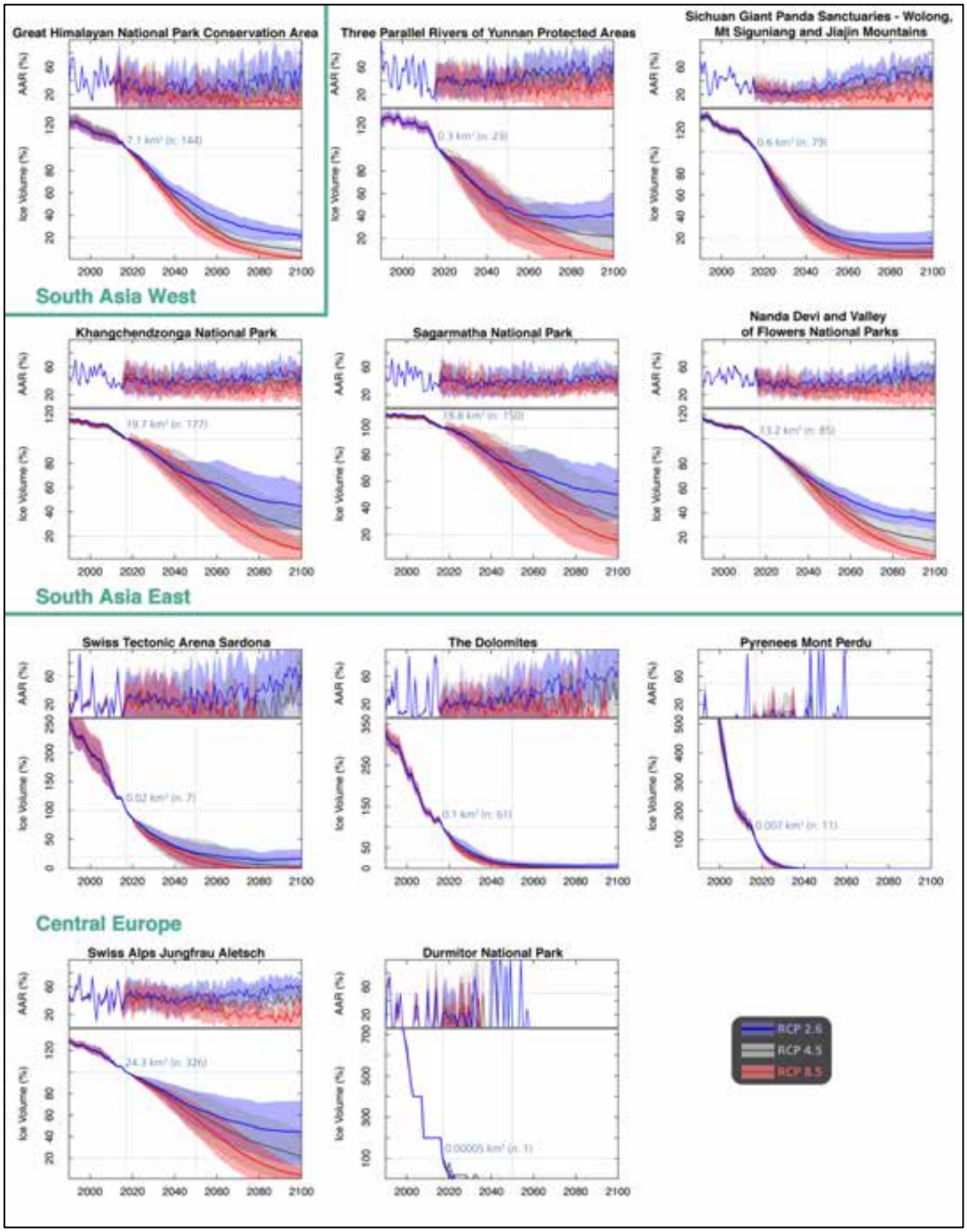
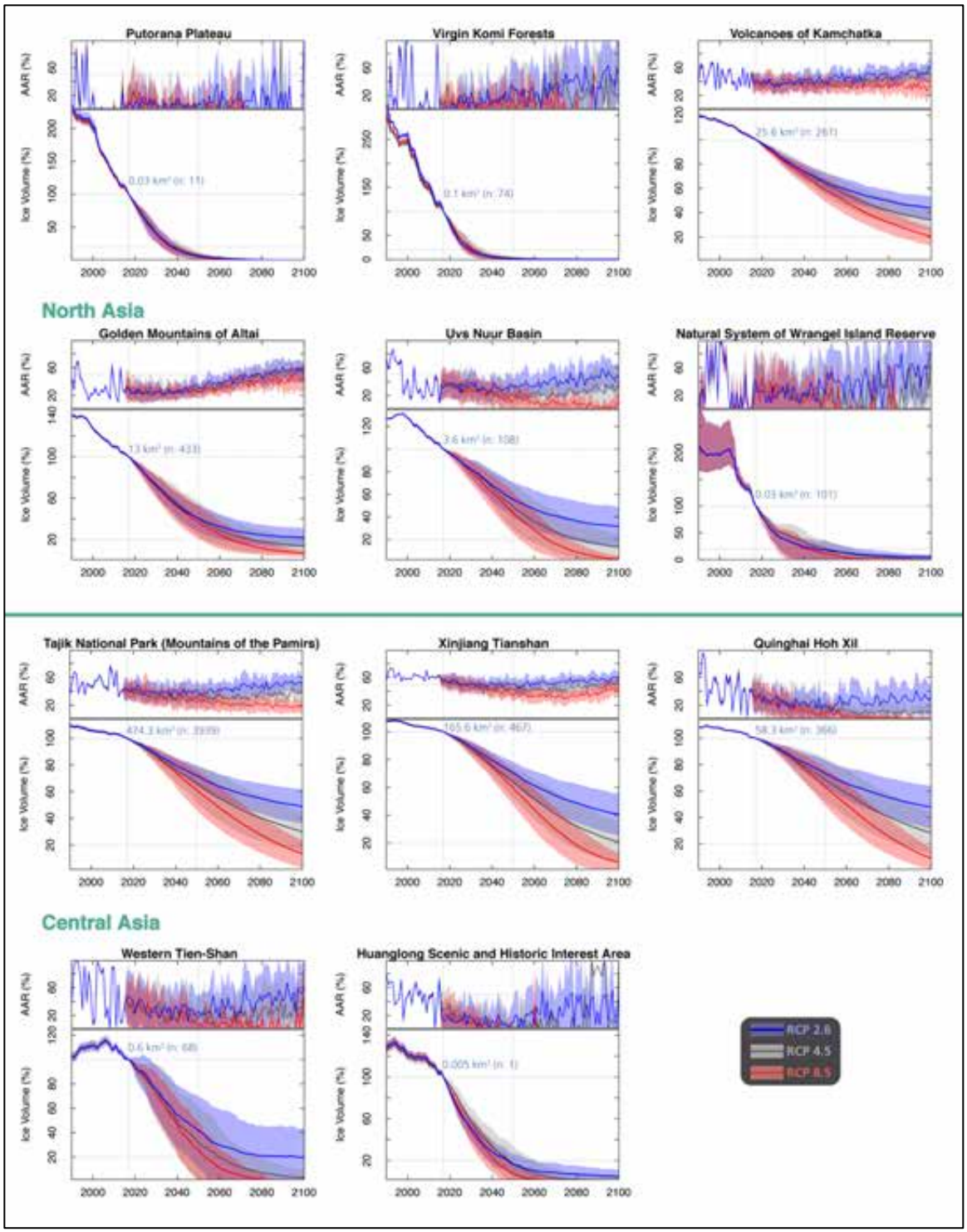


Figure S2. Recent and future evolution of ice volume and accumulation area ratio (AAR) for glaciers in 45 natural World Heritage sites according to different CO_2-emission scenarios (continued on the next three pages). Solid lines correspond to the multi-model mean of 14 GCMs and coloured area to ±1 standard deviation of this mean. Ice volume variations are relative to the 2017 ice volume (in km^3 with the number of glaciers considered in

each evolution diagram) except for Yellowstone National Park*, where these variations are relative to the 2000 volume because the model simulates the melt of the entire volume in the early 2000s.




Great Himalayan National Park Conservation Area
Three Parallel Rivers of Yunnan Protected Areas
Sichuan Giant Panda Sanctuaries - Wolong, Mt Siguniang and Jiajin Mountains
South Asia West
Khangchendzonga National Park
Sagarmatha National Park
Nanda Devi and Valley of Flowers National Parks
South Asia East
Swiss Tectonic Arena Sardona
The Dolomites
Pyrenees Mont Perdu
Central Europe
Swiss Alps Jungfrau Aletsch
Durmitor National Park
AAR (%)
Ice Volume (%)
RCP 2.6
RCP 4.5
RCP 8.5


Putorana Plateau
Virgin Komi Forests
Volcanoes of Kamchatka
North Asia
Golden Mountains of Altai
Uvs Nuur Basin
Natural System of Wrangel Island Reserve
Tajik National Park (Mountains of the Pamirs)
Xinjiang Tianshan
Quinghai Hoh Xil
Central Asia
Western Tien-Shan
Huanglong Scenic and Historic Interest Area
AAR (%)
Ice Volume (%)
RCP 2.6
RCP 4.5
RCP 8.5

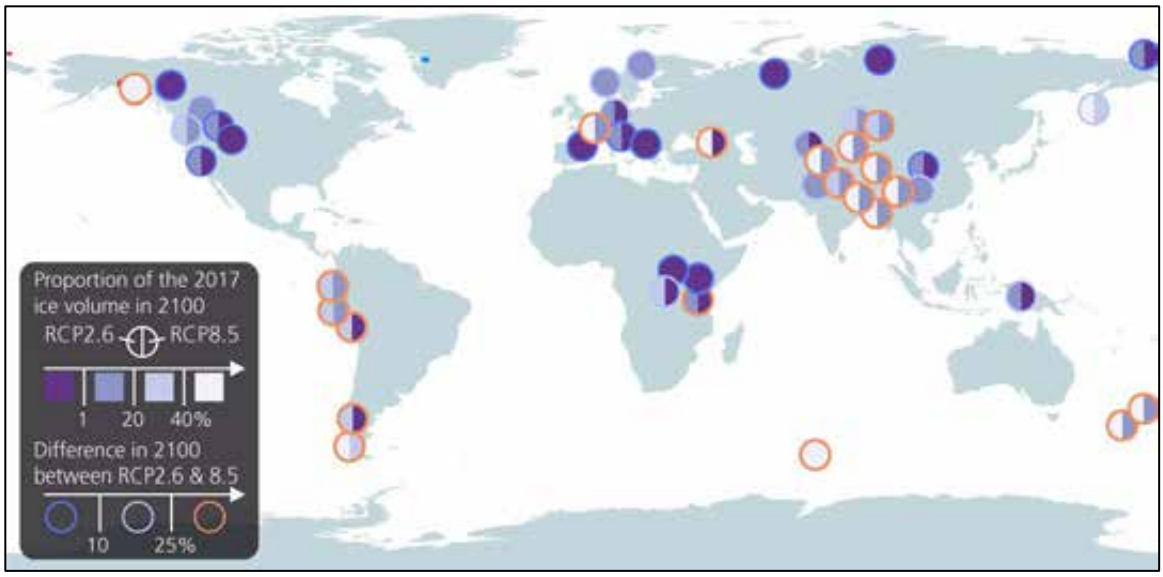


Figure S3. Modelled ice volume by 2100 according to RCP2.6 and RCP8.5 in comparison to the 2017 volume in natural World Heritage sites

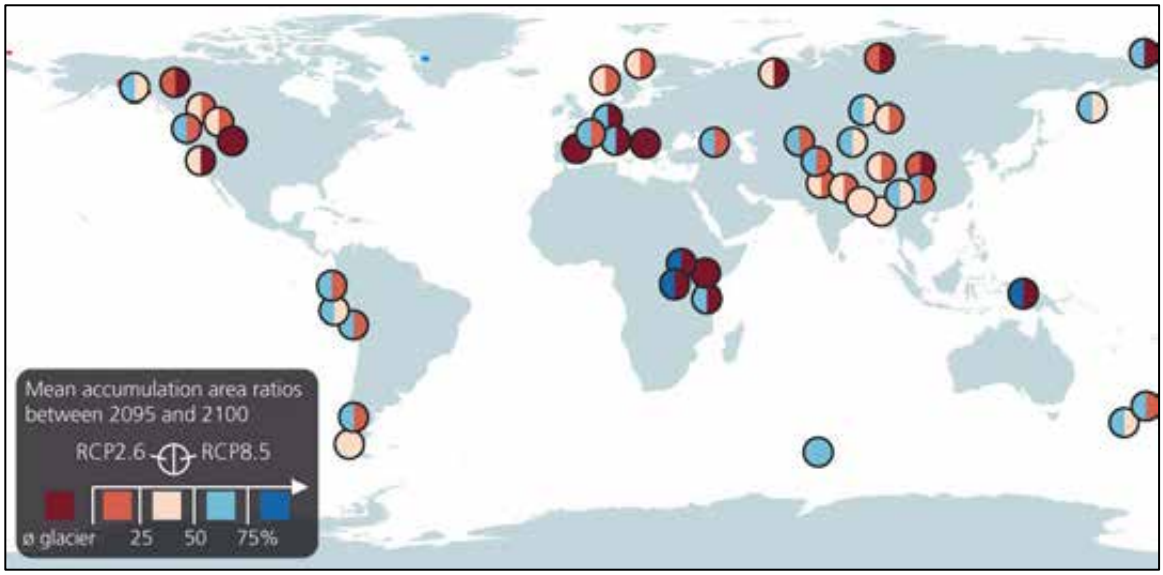


Figure S4. Average accumulation area ratio according to RCP2.6 and RCP8.5 computed for the period 2095-2100 in natural World Heritage sites

	Glaciers (n)	WH glaciers (n)	%	Surface (km^2)	surface within WH (km^2)	%
Antarctic Ice Sheet	1	0	0	12,295,000	0	0
Greenland Ice Sheet	1	1 (part of)	-	1,801,000	3,000	0.2
Other glaciers	215,547	19,038	8.8	705,700	53,000	7.5
All	215,549	19,039	8.8	14,801,700	56,000	0.4

Table S3. Number and area of glaciers in natural World Heritage sites at the global scale. Data for Antarctica, Greenland and other glaciers originate respectively from Fretwell et al. (2013), Kargel et al. (2012) and RGI Consortium (2017).

Conversation Contents

Re: St. Mary VC Exhibits

Deborah Smith <debby_smith@nps.gov>

From:	Deborah Smith <debby_smith@nps.gov>
Sent:	Wed May 22 2019 10:24:12 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

Looks good :-)

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

-------- Original Message --------
From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Date: Wed, May 22, 2019 10:21 AM -0600
To: "Smith, Deborah" <debby_smith@nps.gov>
CC: Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject: Re: St. Mary VC Exhibits

Hey all, how did the install go?

On Mon, May 20, 2019 at 8:10 PM Smith, Deborah <debby_smith@nps.gov> wrote:

> Great! Thanks for the heads up. We'll have an eastside orientation/OSHA happening in the SMVC tomorrow starting at 9 am, so I may be pulled away briefly to help with that, but otherwise I'll be around the VC. Lee will also be around if there are questions.
>
> Thanks again,
> Debby
>
> Debby Smith
> Hudson Bay District Interpreter
> Glacier National Park
> 73 Hudson Bay Road Unit 1
> Browning, MT 59417
> p: (406) 732-7757
>
> I am a *proud* graduate of the GOAL Leadership Academy. Ask me about the program!

On Mon, May 20, 2019 at 4:54 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> Hey Debby and Lee,
>
> Nate should be in the visitor center tomorrow morning to help install the new relief map panels. He has a few things to do on the east side but is roughly aiming to be at the visitor center around 9AM.
>
> -daniel
>
> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
> 406-888-7933

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

Conversation Contents

St. Mary VC Exhibits

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon May 20 2019 16:54:10 GMT-0600 (MDT)
To:	Deborah Smith <debby_smith@nps.gov>, Lee Rademaker <lee_rademaker@nps.gov>
CC:	William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	St. Mary VC Exhibits

Hey Debby and Lee,

Nate should be in the visitor center tomorrow morning to help install the new relief map panels. He has a few things to do on the east side but is roughly aiming to be at the visitor center around 9AM.

-daniel

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Mon May 20 2019 20:09:52 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

Great! Thanks for the heads up. We'll have an eastside orientation/OSHA happening in the SMVC tomorrow starting at 9 am, so I may be pulled away briefly to help with that, but otherwise I'll be around the VC. Lee will also be around if there are questions.

Thanks again,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
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> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed May 22 2019 10:21:10 GMT-0600 (MDT)
To:	"Smith, Deborah" <debby_smith@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
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Conversation Contents

Exhibits at SMVC

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Thu May 16 2019 12:20:32 GMT-0600 (MDT)
To:	Bill Hayden <Bill_Hayden@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Exhibits at SMVC

Hi Bill and Daniel,

I wondered if you had any idea of when we might see the exhibit replacements for SMVC. I just want to make sure that Lee or I are available to get those reinstalled. We have the big influx of folks arriving on Monday, so I just didn't want to forget.

Thanks,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu May 16 2019 12:52:58 GMT-0600 (MDT)
To:	"Smith, Deborah" <debby_smith@nps.gov>
CC:	Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Re: Exhibits at SMVC

We just went and looked at the proofs today. Nate didn't give us an exact day but he's actively working on printing the new ones.

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>
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"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Thu May 16 2019 13:04:34 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Re: Exhibits at SMVC

Ok, thanks for the update.

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
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Conversation Contents

Interp Projects that we need Nate to assist us with.

Attachments:

/10. Interp Projects that we need Nate to assist us with./2.1 GL-07-400 March 2019 Revisions.pdf
/10. Interp Projects that we need Nate to assist us with./2.2 GL-06-300 March 2019 revised.pdf

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Tue Apr 09 2019 09:41:31 GMT-0600 (MDT)
To:	o Hagen <eric_hagen@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Interp Projects that we need Nate to assist us with.

Hi Eric

Here is a rundown of some of the projects that we need to have completed prior to the summer. There will be another late summer list as we complete work.

I have project money to pay some of Nate's time this summer.

Two Medicine Campstore
The exhibit in front of the campstore is stuck in the frame. It appears to have been bent by snow or people sitting on it, or both. The panel that is in there now is one of the old porcelain panels. It is not going to be saved, so if it is destroyed in the removal process, no big deal. We have a new panel that was fabricated in town to go there and it is in the Talley Ho Garage.

Running Eagle Fall Nature Trail
There are exhibits that need to be fabricated and put in place. We have the frames but will need the exhibits installed once Nate makes them. They are similar in size and installation to the ones that he did on the Swiftcurrent Nature Trail last year. There are nine of them.

Headquarters Bicycle Map
The exhibit for the end of the bike path (as people enter the housing area) still needs to be fabricated and installed.

Lake McDonald Lodge
Creekside Reading Room panels have been updated and need to be fabricated and installed. We can handle the installation if you can fabricate them. They will need to be on the thicker Sintra. Do you have Sintra or can we just overlay the existing exhibits with the new vinyl?

Apgar Visitor Center
The services panel for the map needs to be installed prior to the start of the season and we need to fabricate replacement panels for the LEEDS exhibits in the plaza. I think there are four but some might be in multiple locations. I will confirm that and let you know. They are 6" x 12"

Apgar Village
We still need to get that triangular exhibit of three panels installed in front of the old visitor center.

Sun Point
There are three exhibits that need to be installed at Sun Point. Two of them have pads already but there is no mechanism to attach them. They will need bolts put in place. The third one will go along the trail a short distance. I'm not sure how that can be attached and I need to chat with you about that. There are three metal exhibit bases in the Tally Ho garage that are to be used for these exhibits. They were powder-coated at the same time as the HAER exhibits and will blend well with the style we are using there. One panel is fabricated and the other two still need to be done.

St. Mary Visitor Center Exhibits
There are four panel around the topo map that need to be recovered with new/updated information. We think you can probably overlay the existing panels with new vinyl. One of them we will need to talk to you about. It has lights embedded in it and we need to change those around. The information that is there is not correct and needs to be changed as soon as possible.

This summer we will be finishing up some other projects and starting to rehab the exhibits in the North Fork. There will also be four or five more exhibits that go on the Sun Point Nature Trail but those are not completed and will be ready at the end of the summer. There are some other assorted projects that remain from past years that need to be wrapped up as well.

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Tue Apr 09 2019 09:50:56 GMT-0600 (MDT)
To:	"Hayden, William" <bill_hayden@nps.gov>
Subject:	Re: Interp Projects that we need Nate to assist us with.
Attachments:	GL-07-400 March 2019 Revisions.pdf GL-06-300 March 2019 revised.pdf

Here's the final PDFs for the St. Mary exhibits.

Can you review these one more time then we can send them to Eric?

On Tue, Apr 9, 2019 at 9:41 AM Hayden, William <bill_hayden@nps.gov> wrote:

> Hi Eric
>
> Here is a rundown of some of the projects that we need to have completed prior to the

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--
Daniel Lombardi
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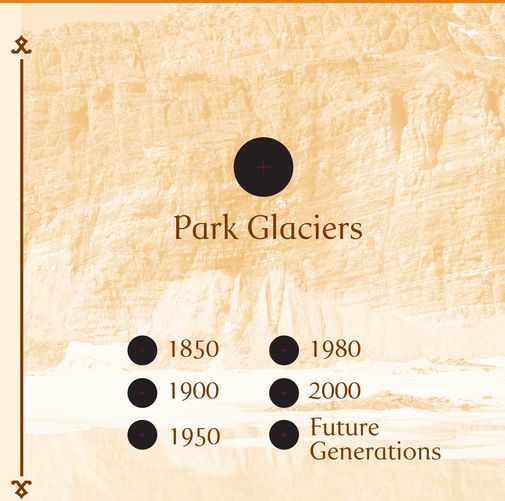
Glacier National Park
406-888-7933

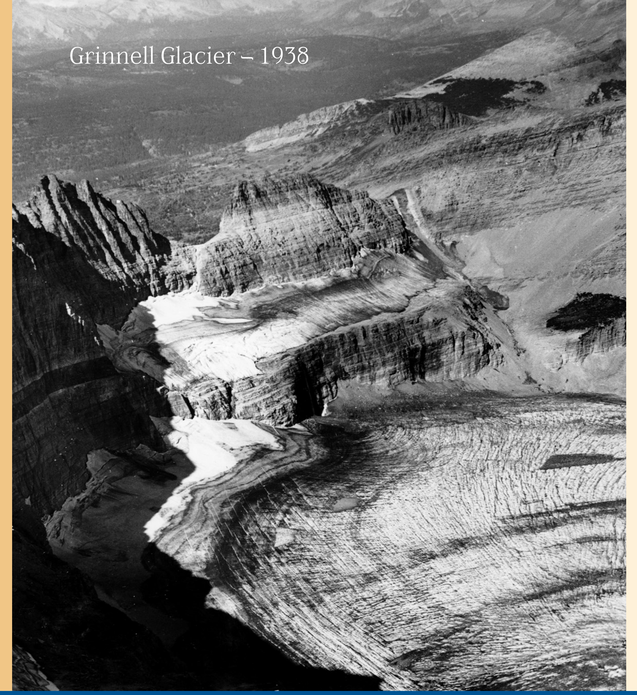
GOODBYE TO THE GLACIERS

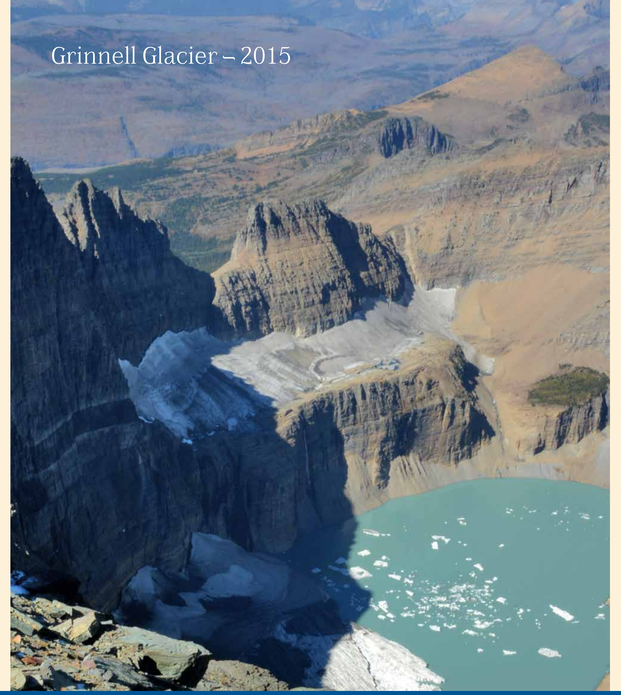
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. Today, they are all rapidly shrinking due to human-caused climate change. When they will completely disappear, however, is difficult to predict.



Glaciers are moving masses of ice. The glaciers that shaped the park were massive. During the Pleistocene—12,000–130,000 years ago—the glaciers covering this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

In 1850 there were about 150 glaciers in the park. In 2015, 26 named glaciers were active in the park.

Some glaciers melt faster than others, but one thing is consistent: all the glaciers are shrinking. Grinnell Glacier, located high in the Many Glacier valley, has lost 45% of its area in recent decades.

GLACIERS ON THE MOVE

Conversation Contents

Map

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Sat Mar 16 2019 12:30:48 GMT-0600 (MDT)
To:	Bill Hayden <Bill_Hayden@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
CC:	"Rademaker, Lee" <lee_rademaker@nps.gov>
Subject:	Map

Hi Bill and Daniel,

As a follow-up from our conversation about the St. Mary glacier exhibits, Lee checked while he was at the VC the other day and as best as he could tell with the sun shining on the map, 25 lights were illuminated for "2000." There is a light for Siyeh on the map though and Lee should be able to configure the wiring to make it also light up with the "2000" set. So, we'd be safe to change "2000" to either "2015" (when it was last officially updated?) or "2019" if that's what Lisa agrees is the current number for that year. Ignoring those pesky rock glaciers, of course 😉

We'll be able to bring over the relief map panel for "Goodbye to the Glaciers." After looking at it and realizing the little bit of extra trouble to remove the lights/button from the panel, we'll just bring that one and see how Eric is able to retrofit the new panel. Depending on how it looks, we can decide whether we should bring the other panels over to match (instead of taking them all off now) or whether it's too subtle of a difference for visitors to even notice.

We'll be coming over this Thursday for a meeting, so we'll just leave the panel in Daniel's office so it'll be there for you when you're ready.

Thanks,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

I am a *proud* graduate of the GOAL Leadership Academy. Ask me about the program!

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>

Sent:	Mon Mar 18 2019 10:45:25 GMT-0600 (MDT)
To:	"Smith, Deborah" <debby_smith@nps.gov>
CC:	Bill Hayden <Bill_Hayden@nps.gov>, "Rademaker, Lee" <lee_rademaker@nps.gov>
Subject:	Re: Map

Thanks for the update!

I agree, let's just start with the two panels that need fixed and see if we need to make the colors match later.

Bill and I are out of the office this week but Bill can send the updated PDFs to Eric and take the panels to him next week.

-daniel

On Sat, Mar 16, 2019 at 12:31 PM Smith, Deborah <debby_smith@nps.gov> wrote:

> Hi Bill and Daniel,
>
> As a follow-up from our conversation about the St. Mary glacier exhibits, Lee checked while he was at the VC the other day and as best as he could tell with the sun shining on the map, 25 lights were illuminated for "2000." There is a light for Siyeh on the map though and Lee should be able to configure the wiring to make it also light up with the "2000" set. So, we'd be safe to change "2000" to either "2015" (when it was last officially updated?) or "2019" if that's what Lisa agrees is the current number for that year. Ignoring those pesky rock glaciers, of course 😉
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>
> Debby Smith
> Hudson Bay District Interpreter
> Glacier National Park
> 73 Hudson Bay Road Unit 1
> Browning, MT 59417
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>
> I am a *proud* graduate of the GOAL Leadership Academy. Ask me about the program!

--

Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

Conversation Contents

St. Mary Map

Attachments:

/12. St. Mary Map/1.1 IMG_2062.JPG
/12. St. Mary Map/1.2 ATT00001
/12. St. Mary Map/1.3 IMG_2063.JPG
/12. St. Mary Map/1.4 ATT00002
/12. St. Mary Map/1.5 IMG_2064.JPG
/12. St. Mary Map/1.6 ATT00003
/12. St. Mary Map/1.7 IMG_2065.JPG
/12. St. Mary Map/1.8 ATT00004

Lee Rademaker <lee.rademaker@gmail.com>

From:	Lee Rademaker <lee.rademaker@gmail.com>
Sent:	Thu Mar 22 2018 15:47:13 GMT-0600 (MDT)
To:	<Bill_hayden@nps.gov>
Subject:	St. Mary Map
Attachments:	IMG_2062.JPG ATT00001 IMG_2063.JPG ATT00002 IMG_2064.JPG ATT00003 IMG_2065.JPG ATT00004

Here are some shots of the exhibit.

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Thu Mar 22 2018 16:10:55 GMT-0600 (MDT)
To:	Lee Rademaker <lee.rademaker@gmail.com>
Subject:	Re: St. Mary Map

Thanks

On Thu, Mar 22, 2018 at 3:47 PM, Lee Rademaker <lee.rademaker@gmail.com> wrote:

> Here are some shots of the exhibit.

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

GOODBYE TO THE GLACIERS

The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. They are now rapidly shrinking due to human-caused climate change. Computer models indicate the glaciers will all be gone by the year 2020.

Glacier National Park was named for the sculpting actions of the Pleistocene glaciers that covered this landscape 12,000 to 130,000 years ago.

Park glaciers between 1850 and 2020

- 1850
- 1900
- 1950
- 1980
- 2000
- 2020 *(projected)*

Park glaciers between 1850 and 2020

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Conversation Contents

Wayside Exhibit Projects

Attachments:

/1. Wayside Exhibit Projects/1.1 waysides for jeff.docx

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Tue Jun 11 2019 13:33:22 GMT-0600 (MDT)
To:	Connie Stahr <connie_stahr@nps.gov>
CC:	Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Wayside Exhibit Projects
Attachments:	waysides for jeff.docx

Attached is a brief outline of ongoing and upcoming exhibit projects around the park. I have listed the PMIS numbers for the ones that are included in SCC proposals.

This list does not include all exhibits and does not include interior exhibits in the visitor centers. That list will take more time to generate.

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Wed Jun 19 2019 14:35:20 GMT-0600 (MDT)
To:	"Hayden, William" <bill_hayden@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: Wayside Exhibit Projects

Thanks, Bill!

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
~~~~~~~~~~~~~~~~~~~~~~~~~~

406-888-7930

On Tue, Jun 11, 2019 at 1:33 PM Hayden, William <bill_hayden@nps.gov> wrote:

> Attached is a brief outline of ongoing and upcoming exhibit projects around the park. I have listed the PMIS numbers for the ones that are included in SCC proposals.
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> --
> **Bill Hayden**
> Interpretive Specialist
> Glacier National Park
> West Glacier, MT 59936
> 406-888-7927

Conversation Contents

If visitors ask when the glaciers will be gone:

Attachments:

/2. If visitors ask when the glaciers will be gone:/1.1 STMARY-VC-EXHIBIT-1-OLD.png
/2. If visitors ask when the glaciers will be gone:/1.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/2. If visitors ask when the glaciers will be gone:/1.3 STMARY-VC-EXHIBIT-2-OLD.png
/2. If visitors ask when the glaciers will be gone:/1.4 STMARY-VC-EXHIBIT-2-UPDATED.png
/2. If visitors ask when the glaciers will be gone:/2.1 STMARY-VC-EXHIBIT-1-OLD.png
/2. If visitors ask when the glaciers will be gone:/2.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/2. If visitors ask when the glaciers will be gone:/2.3 STMARY-VC-EXHIBIT-2-OLD.png
/2. If visitors ask when the glaciers will be gone:/2.4 STMARY-VC-EXHIBIT-2-UPDATED.png

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Fri Jun 14 2019 11:49:40 GMT-0600 (MDT)
To:	Marc Neidig <marc_neidig@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>
CC:	William Hayden <bill_hayden@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>
Subject:	If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

If visitors ask when the glaciers will be gone:
Data show that in 1966, the park had 35 named glaciers large enough to be considered active. By 2015, only 26 named glaciers remained in that category. The average area reduction was 39 percent, though some lost as much as 85 percent. This trend of glacier retreat is expected to continue as temperatures rise. Some small remnant ice may persist late into the 21st century or even beyond, depending on future rates of climate change.

These updated webpages are your best secondary sources for information on the park's glaciers:

- https://www.nps.gov/glac/learn/nature/melting-glaciers.htm
- https://www.nps.gov/glac/learn/nature/how-to-see-a-glacier.htm
- https://www.nps.gov/glac/learn/nature/glacial-geology.htm

Background on previously used prediction dates:
A USGS geospatial model published in a 2003 paper predicted that Blackfoot and Jackson would be gone by 2030. Because these are two of the larger glaciers in the park (2nd and 6th respectively in 1966), it was extrapolated that if they were gone, the rest of the glaciers in the park would be gone too. The predicted date of 2030 was put on several exhibits throughout the park, including in the Apgar and St. Mary Visitor Center plazas.

Further research in the late 2000s (page 80) revealed that Jackson and Blackfoot glaciers were melting even faster than the rate predicted in the 2003 geospatial model. So fast, in fact, that if the rate continued they would be gone by 2020. It was then extrapolated that if Blackfoot and Jackson were gone by 2020, the rest of the glaciers in the park would be gone too. The 2020 date was then put on two exhibits outside the Logan Pass Visitor Center and on two exhibits inside the St. Mary Visitor Center (see below).

In May, 2019 the St. Mary Visitor Center exhibits were updated to reflect the analyses, data, and insights that have emerged since 2010. This latest research shows shrinking of all the park's glaciers but in ways far more complicated, and interesting, than expressed in the early 2000s. In the three places that used the 2020 date, the exhibits now say: *"Future Generations;" "When they will completely disappear, however, depends on how and when we act;"* and *"Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking."* (See images below.)

There are plans to update all the other exhibits (at the Logan Pass, Apgar, and St. Mary visitor centers) that use the 2020 and 2030 dates as time and funding allows.

STMARY-VC-EXHIBIT-1-OLD.png
STMARY-VC-EXHIBIT-1-UPDATED.png
STMARY-VC-EXHIBIT-2-OLD.png

STMARY-VC-EXHIBIT-2-UPDATED.png

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Fri Jun 14 2019 11:57:02 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

Thanks for pulling this together.

On Fri, Jun 14, 2019 at 11:50 AM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> **If visitors ask when the glaciers will be gone:**
> *Data show that in 1966, the park had 35 named glaciers large enough to be considered active. By 2015, only 26 named glaciers remained in that category. The average area reduction was 39 percent, though some lost as much as 85 percent. This trend of glacier retreat is expected to continue as temperatures rise. Some small remnant ice may persist late into the 21st century or even beyond, depending on future rates of climate change.*
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STMARY-VC-EXHIBIT-1-UPDATED.png
STMARY-VC-EXHIBIT-2-OLD.png
STMARY-VC-EXHIBIT-2-UPDATED.png

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

Conversation Contents

Exhibit text and/or photos ASAP?

Attachments:

/3. Exhibit text and/or photos ASAP?/2.1 GL-07-400rev2.pdf
/3. Exhibit text and/or photos ASAP?/2.2 GL-07-400 May 2019 Revisions.pdf
/3. Exhibit text and/or photos ASAP?/2.3 GL-06-300 updated MAY 2019.pdf
/3. Exhibit text and/or photos ASAP?/2.4 GL-06-300rev1.pdf
/3. Exhibit text and/or photos ASAP?/3.1 GL-07-400rev2.pdf
/3. Exhibit text and/or photos ASAP?/3.2 GL-07-400 May 2019 Revisions.pdf
/3. Exhibit text and/or photos ASAP?/3.3 GL-06-300 updated MAY 2019.pdf
/3. Exhibit text and/or photos ASAP?/3.4 GL-06-300rev1.pdf

Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Sat Jun 08 2019 15:05:54 GMT-0600 (MDT)
To:	lee_rademaker@nps.gov, debby_smith@nps.gov
CC:	Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject:	Exhibit text and/or photos ASAP?

Hey Lee and Debby - Are either of you working today or tomorrow? There are some media outlets reporting about our Glacier exhibit updates and I'd like to get a sense of how things looked before and after so we can put some info on the web if needed to clear up confusion. My guess is that by Monday morning, main stream media will be calling. If you have text or photos or anything, I would really appreciate it. Cc to Tracy and Bill as well. Thanks all. Sent from my iPad

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Sat Jun 08 2019 16:20:37 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, "Mensch, D" <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Here are some attachments and some background.

The exhibits in the St. Mary Visitor Center were probably installed in 2010. There had been several planning and design meetings with Harpers Ferry Center personnel in the several years

previous. Mark Wagner was the lead on the exhibit redesigns. Sheri Forbes was the Chief of Interpretation. I was actually not involved in any aspect of the project or meetings from start to finish, so my memory on the exact dates is fuzzy. My guess on the year is based on the final planning document from the fabricator of the exhibits. The planning and design most surely happened much prior to that date. Mark Wagner may know more specifics.

In any case the exhibits that deal with glacial retreat were based on the USGS information that was available at that time. Since then their research has continued and evolved to include a more refined picture of glaciers in the park. Like much of scientific research, there are often not concrete black and white answers to basic questions, and that is often hard for some people to grapple with.

In the late summer, or fall, of 2017 staff from the USGS informed us, the media staff, that there were dates in the exhibits near the relief map at St. Mary that were not consistent with current research and asked that we change them. We were unable to do that for the 2018 season. At the end of the season we removed the exhibits and made changes to the original files. Those changes went through review by NPS and USGS staff and our sign shop was able to fabricate them and have them installed just prior to the opening of the Visitor Center this spring. Attached you should find the new exhibits and the former exhibits as PDF files.

There are also exhibits at the Apgar and St. Mary Visitor Center plazas, outside, that have dates that need changing. Those exhibits date from 2007. There are two exhibits that I know of at Logan Pass that likewise have these dates and should be changed out. In 2018 two new glacier exhibits replaced the one exhibit at Jackson Glacier Overlook. The old one had the 2030 date on it as well. It also contained images from the computer projection model, that was based on USGS work published in the early 2000s, I think 2003. This oldexhibit was designed in 2006 in coordination with Leigh Welling, who was in charge of the Crown of the Continent Research Learning Center at the time. I remember the date because I worked on refining her files while I was in Seattle that entire summer. She went from Glacier to a position in Colorado for the Natural Resources Division, where she dealt specifically with climate change issues.

A more complete review of other wayside exhibits will show mentions of climate change and some may have dates, although none come to mind at the moment. I can provide copies of these other exhibits if you wish, but I don't want to overload this particular email. We have them to view when needed.

Exhibit GL-07-400 May 2019 Revisions.pdf is the exhibit at the relief map that has the button to push for locations of the glaciers. It does not mention a specific date for the complete glacial melt. GL-07-400rev2.pdf is the original file as installed when the rest of the exhibits went in.

Exhibit GL-06-300rev1.pdf is the as installed original exhibit that is in front of one of the windows looking out at the mountains. It mentions also that 202 is the year the glaciers will be melted. GL-06-300 updated MAY 2019.pdf is the new file that was installed last month.

Daniel/Tracy feel free to provide any details or updates that I may have missed or gotten wrong.

On Sat, Jun 8, 2019 at 3:05 PM Lauren Alley <lauren_alley@nps.gov> wrote:

> Hey Lee and Debby -
>
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> Sent from my iPad

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Mon Jun 10 2019 08:00:57 GMT-0600 (MDT)
To:	"Mow, Jeff" <jeff_mow@nps.gov>, Connie Stahr <connie_stahr@nps.gov>
CC:	"Alley, Lauren" <lauren_alley@nps.gov>, Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Fwd: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Jeff,

For our discussion and your information. If we need additional detail in regard to timing, I could reach out to Mark Wagner and/or HFC.

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930

---------- Forwarded message ---------
From: **Hayden, William** <bill_hayden@nps.gov>
Date: Sat, Jun 8, 2019 at 4:20 PM
Subject: Re: Exhibit text and/or photos ASAP?
~~~~~~~~~~~~~~~~~~~~~~~~~

To: Lauren Alley <lauren_alley@nps.gov>
Cc: Lee Rademaker <lee_rademaker@nps.gov>, Mensch, D <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>

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--

Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

Conversation Contents

Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Sat Jun 08 2019 16:31:30 GMT-0600 (MDT)
To:	Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Bill,
Thank you so very much for the comprehensive information you provided in the other email you sent, with exhibit attachments. Note this email from Jeff and some of the additional information that he will also be looking for us to provide on Monday. In particular it is apparent that Jeff has an interest in seeing how these may associate with deferred maintenance and the maintenance backlog. You went above and beyond the call of duty today! Thank you so much!

---------- Forwarded message ---------
From: **Jeff Mow** <jeff_mow@nps.gov>
Date: Sat, Jun 8, 2019, 3:54 PM
Subject: Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage
To: Lauren Alley <lauren_alley@nps.gov>
Cc: <dan_fagre@usgs.gov>, <Melissa_Sladek@nps.gov>, <tara_carolin@nps.gov>, <tracy_ammerman@nps.gov>, <phil_wilson@nps.gov>

All

Debby and I touched base on this yesterday and we said we'd circle up on the process on Monday. A couple of things I'd like to know

1) how old are these exhibits
2) when did we put these into pmis for replacement funding
3) how many exhibits overall do we have in pmis for cyclic funding replacement
4) am I correct in assuming that the lion's share of exhibit panels that make reference to When the glaciers will disappear use the 2030 date. The 2020 date is an outlier.

To me there is a backstory that may have a connection to DM. We have so many trails, roads, restrooms, campgrounds, water systems, and wayside exhibits that are in line for replacement or rehabilitation and as we all know it can takes years for things to move up in the priority list.

I have no idea if these exhibits are in The system like the interpretive waysides are so this theme may not apply.

Sent from my iPhone

On Jun 8, 2019, at 3:12 PM, Lauren Alley <lauren_alley@nps.gov> wrote:

All -

I am circling back with you on what WASO and DOI have proposed below. From media outlets, it appears they're already using it (the stuff in gray text that the park didn't develop). The story has gone fairly viral in the last 24 hours.

Dan - do you want us to use this, or something else?

From park perspective I'm hoping to track down exhibit text so we can hopefully proactively address this.

My main objective is to identify exactly what NPS/USGS said about 2020 and publicly acknowledge that via website to clear up any confusion and for transparency. Certainly nobody wants to "quietly" do something or hide something. If anyone has any proposed text for this specific point, I'd welcome it.

Thanks to anyone who can provide input over the weekend. My guess is that by Monday at 8 am, we're going to get even more calls.

Sent from my iPad

Begin forwarded message:

> **From:** "Kupper, Kathy" <kathy_kupper@nps.gov>
> **Date:** June 7, 2019 at 3:24:56 PM MDT
> **To:** "Block, Molly" <molly_block@ios.doi.gov>
> **Cc:** April Slayton <april_slayton@nps.gov>, "Barnum, Jeremy" <jeremy_barnum@nps.gov>, Karen Armstrong <karmstrong@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Paul Laustsen <plaustsen@usgs.gov>, Ryan McClymont <rmcclymont@usgs.gov>, Catherine Puckett <cpuckett@usgs.gov>
> **Subject: Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage**
>
> Hi Molly,
>
> April and I are OK with the statement. We are looping in park staff and a couple of other SMEs for awareness and their input on the statement. Dan Fagre from USGS (dan_fagre@usgs.gov) is the SME that can also take calls if needed.
>
> Thank you,
> Kathy
>
> Kathy Kupper
> Public Affairs Specialist
> Office of Communications
> National Park Service
> (202)513-7263
> www.nps.gov
>
> The National Park Service cares for special places saved by the American people so that all may experience our heritage.

EXPERIENCE YOUR AMERICA ®

On Fri, Jun 7, 2019 at 5:00 PM Block, Molly <molly_block@ios.doi.gov> wrote:

> Adding the Park Service. Let's get a desk statement we can send around. Here's what I shared with the Daily Caller:
>
> Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.
>
> The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.
>
> USGS regularly publicizes their research efforts. The National Park Service does not typically issue press releases for new interpretive displays or park signage.
>
> The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.
>
> On Fri, Jun 7, 2019 at 4:53 PM Karen Armstrong <karmstrong@usgs.gov> wrote:
>
>> How would you like to handle?
>>
>> Sent from my iPhone
>>
>> Begin forwarded message:
>>
>>> **From:** Cheyenne MacDonald <Cheyenne.Macdonald@mailonline.com>
>>> **Date:** June 7, 2019 at 4:48:07 PM EDT
>>> **To:** "karmstrong@usgs.gov" <karmstrong@usgs.gov>
>>> **Subject: [EXTERNAL] Daily Mail Inquiry - National Park Signage**
>>>
>>> Hi Karen! My name is Cheyenne, I'm the Science & Tech Editor at Dailymail.com. I'm reaching out in regards to a report that's been going around today, was hoping to get some additional context and verify the claims being made.
>>>
>>> The report, linked here, https://dailycaller.com/2019/06/07/national-park-glacier-warnings/ , claims signs at Glacier National Park that warned glaciers will disappear by 2020 due to climate change have been 'quietly removed' after 'several winters of heavy snowfall threw off climate model projections.'

I would appreciate if you could clarify a few points:

-Have the signs really been changed? If so, when and why

-What do the latest models suggest about the state of glaciers in the park?

-Is there any weight to claims that glaciers have grown in recent years due to heavier snowfall?

Any additional information you can provide on the subject would be great.

Thanks so much.

Best,

Cheyenne

Cheyenne MacDonald

US Science & Technology Editor

Daily Mail Online | @_cheymac

51 Astor Place, 9th Floor, New York, NY 10003

<image001.png>

<image002.png>

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--
Molly Block
Press Secretary
U.S. Department of the Interior

Conversation Contents

Re: Exhibit text and/or photos ASAP?

Deborah Smith <debby_smith@nps.gov>

From:	Deborah Smith <debby_smith@nps.gov>
Sent:	Sat Jun 08 2019 16:03:03 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>, lee_rademaker@nps.gov
CC:	Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject:	Re: Exhibit text and/or photos ASAP?

Actually Bill (or Daniel for sure) should have all of this. I'm in town right now, but I can look when I get back and I think I also have the new panel in my email from when Daniel sent it to Lee and I to proof. I'm around this weekend, but Lee is back in Helena this weekend.

I'll be in touch...

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

-------- Original Message --------
From: Lauren Alley <lauren_alley@nps.gov>
Date: Sat, June 08, 2019 3:05 PM -0600
To: lee_rademaker@nps.gov, debby_smith@nps.gov
CC: Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject: Exhibit text and/or photos ASAP?

Hey Lee and Debby -

Are either of you working today or tomorrow?

There are some media outlets reporting about our Glacier exhibit updates and I'd like to get a sense of how things looked before and after so we can put some info on the web if needed to clear up confusion.

My guess is that by Monday morning, main stream media will be calling.

If you have text or photos or anything, I would really appreciate it.

Cc to Tracy and Bill as well.

Thanks all.

Sent from my iPad

Conversation Contents

academic sources I've been using to understand how long the glaciers will be active

Attachments:

/6. academic sources I've been using to understand how long the glaciers will be active/1.1 Brown_2010_GPC (1).pdf
/6. academic sources I've been using to understand how long the glaciers will be active/1.2 Bosson_et_al-2019-Earth's_Future.pdf
/6. academic sources I've been using to understand how long the glaciers will be active/1.3 Clarke_2015_NatureGeoscience.pdf
/6. academic sources I've been using to understand how long the glaciers will be active/1.4 Huss_2017_EarthsFuture.pdf
/6. academic sources I've been using to understand how long the glaciers will be active/1.5 Bosson_et_al_2019_EarthsFuture_Suppporting_Information.docx

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Sat Jun 08 2019 15:59:36 GMT-0600 (MDT)
To:	William Hayden <bill_hayden@nps.gov>
Subject:	academic sources I've been using to understand how long the glaciers will be active
Attachments:	Brown_2010_GPC (1).pdf Bosson_et_al-2019-Earth's_Future.pdf Clarke_2015_NatureGeoscience.pdf Huss_2017_EarthsFuture.pdf Bosson_et_al_2019_EarthsFuture_Suppporting_Information.docx

Bosson 2019 has charts showing predictions for glaciers around the world
Bosson 2019 Supporting Information has predictions for glaciers in Glacier National Park
Brown 2010 has predictions for Sperry Glacier
Clarke 2015 has regional glacier predictions
Huss 2017 has more regional glacier predictions

Conversation Contents

Re: St. Mary VC Exhibits

Deborah Smith <debby_smith@nps.gov>

From:	Deborah Smith <debby_smith@nps.gov>
Sent:	Wed May 22 2019 10:24:12 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

Looks good :-)

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

-------- Original Message --------
From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Date: Wed, May 22, 2019 10:21 AM -0600
To: "Smith, Deborah" <debby_smith@nps.gov>
CC: Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject: Re: St. Mary VC Exhibits

Hey all, how did the install go?

On Mon, May 20, 2019 at 8:10 PM Smith, Deborah <debby_smith@nps.gov> wrote:

> Great! Thanks for the heads up. We'll have an eastside orientation/OSHA happening in the SMVC tomorrow starting at 9 am, so I may be pulled away briefly to help with that, but otherwise I'll be around the VC. Lee will also be around if there are questions.
>
> Thanks again,
> Debby
>
> Debby Smith
> Hudson Bay District Interpreter
> Glacier National Park
> 73 Hudson Bay Road Unit 1
> Browning, MT 59417
> p: (406) 732-7757
>
> I am a *proud* graduate of the GOAL Leadership Academy. Ask me about the program!

On Mon, May 20, 2019 at 4:54 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> Hey Debby and Lee,
>
> Nate should be in the visitor center tomorrow morning to help install the new relief map panels. He has a few things to do on the east side but is roughly aiming to be at the visitor center around 9AM.
>
> -daniel
>
> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
> 406-888-7933

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

Conversation Contents

St. Mary VC Exhibits

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon May 20 2019 16:54:10 GMT-0600 (MDT)
To:	Deborah Smith <debby_smith@nps.gov>, Lee Rademaker <lee_rademaker@nps.gov>
CC:	William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	St. Mary VC Exhibits

Hey Debby and Lee,

Nate should be in the visitor center tomorrow morning to help install the new relief map panels. He has a few things to do on the east side but is roughly aiming to be at the visitor center around 9AM.

-daniel

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Mon May 20 2019 20:09:52 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

Great! Thanks for the heads up. We'll have an eastside orientation/OSHA happening in the SMVC tomorrow starting at 9 am, so I may be pulled away briefly to help with that, but otherwise I'll be around the VC. Lee will also be around if there are questions.

Thanks again,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
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p: (406) 732-7757

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> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
> 406-888-7933

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed May 22 2019 10:21:10 GMT-0600 (MDT)
To:	"Smith, Deborah" <debby_smith@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

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Daniel Lombardi
Visual Information Specialist
Glacier National Park
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Conversation Contents

Exhibits at SMVC

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Thu May 16 2019 12:20:32 GMT-0600 (MDT)
To:	Bill Hayden <Bill_Hayden@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Exhibits at SMVC

Hi Bill and Daniel,

I wondered if you had any idea of when we might see the exhibit replacements for SMVC. I just want to make sure that Lee or I are available to get those reinstalled. We have the big influx of folks arriving on Monday, so I just didn't want to forget.

Thanks,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu May 16 2019 12:52:58 GMT-0600 (MDT)
To:	"Smith, Deborah" <debby_smith@nps.gov>
CC:	Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Re: Exhibits at SMVC

We just went and looked at the proofs today. Nate didn't give us an exact day but he's actively working on printing the new ones.

On Thu, May 16, 2019 at 12:20 PM Smith, Deborah <debby_smith@nps.gov> wrote:

> Hi Bill and Daniel,
>
> I wondered if you had any idea of when we might see the exhibit replacements for SMVC. I just want to make sure that Lee or I are available to get those reinstalled. We have the big

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>
> Debby Smith
> Hudson Bay District Interpreter
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Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Thu May 16 2019 13:04:34 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Re: Exhibits at SMVC

Ok, thanks for the update.

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
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>
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Daniel Lombardi
Visual Information Specialist
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Conversation Contents

Interp Projects that we need Nate to assist us with.

Attachments:

/10. Interp Projects that we need Nate to assist us with./2.1 GL-07-400 March 2019 Revisions.pdf
/10. Interp Projects that we need Nate to assist us with./2.2 GL-06-300 March 2019 revised.pdf

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Tue Apr 09 2019 09:41:31 GMT-0600 (MDT)
To:	o Hagen <eric_hagen@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Interp Projects that we need Nate to assist us with.

Hi Eric

Here is a rundown of some of the projects that we need to have completed prior to the summer. There will be another late summer list as we complete work.

I have project money to pay some of Nate's time this summer.

Two Medicine Campstore
The exhibit in front of the campstore is stuck in the frame. It appears to have been bent by snow or people sitting on it, or both. The panel that is in there now is one of the old porcelain panels. It is not going to be saved, so if it is destroyed in the removal process, no big deal. We have a new panel that was fabricated in town to go there and it is in the Talley Ho Garage.

Running Eagle Fall Nature Trail
There are exhibits that need to be fabricated and put in place. We have the frames but will need the exhibits installed once Nate makes them. They are similar in size and installation to the ones that he did on the Swiftcurrent Nature Trail last year. There are nine of them.

Headquarters Bicycle Map
The exhibit for the end of the bike path (as people enter the housing area) still needs to be fabricated and installed.

Lake McDonald Lodge
Creekside Reading Room panels have been updated and need to be fabricated and installed. We can handle the installation if you can fabricate them. They will need to be on the thicker Sintra. Do you have Sintra or can we just overlay the existing exhibits with the new vinyl?

Apgar Visitor Center
The services panel for the map needs to be installed prior to the start of the season and we need to fabricate replacement panels for the LEEDS exhibits in the plaza. I think there are four but some might be in multiple locations. I will confirm that and let you know. They are 6" x 12"

Apgar Village
We still need to get that triangular exhibit of three panels installed in front of the old visitor center.

Sun Point
There are three exhibits that need to be installed at Sun Point. Two of them have pads already but there is no mechanism to attach them. They will need bolts put in place. The third one will go along the trail a short distance. I'm not sure how that can be attached and I need to chat with you about that. There are three metal exhibit bases in the Tally Ho garage that are to be used for these exhibits. They were powder-coated at the same time as the HAER exhibits and will blend well with the style we are using there. One panel is fabricated and the other two still need to be done.

St. Mary Visitor Center Exhibits
There are four panel around the topo map that need to be recovered with new/updated information. We think you can probably overlay the existing panels with new vinyl. One of them we will need to talk to you about. It has lights embedded in it and we need to change those around. The information that is there is not correct and needs to be changed as soon as possible.

This summer we will be finishing up some other projects and starting to rehab the exhibits in the North Fork. There will also be four or five more exhibits that go on the Sun Point Nature Trail but those are not completed and will be ready at the end of the summer. There are some other assorted projects that remain from past years that need to be wrapped up as well.

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Tue Apr 09 2019 09:50:56 GMT-0600 (MDT)
To:	"Hayden, William" <bill_hayden@nps.gov>
Subject:	Re: Interp Projects that we need Nate to assist us with.
Attachments:	GL-07-400 March 2019 Revisions.pdf GL-06-300 March 2019 revised.pdf

Here's the final PDFs for the St. Mary exhibits.

Can you review these one more time then we can send them to Eric?

On Tue, Apr 9, 2019 at 9:41 AM Hayden, William <bill_hayden@nps.gov> wrote:

> Hi Eric
>
> Here is a rundown of some of the projects that we need to have completed prior to the

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--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

Conversation Contents

If visitors ask when the glaciers will be gone:

Attachments:

/1. If visitors ask when the glaciers will be gone:/1.1 STMARY-VC-EXHIBIT-1-OLD.png
/1. If visitors ask when the glaciers will be gone:/1.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/1.3 STMARY-VC-EXHIBIT-2-OLD.png
/1. If visitors ask when the glaciers will be gone:/1.4 STMARY-VC-EXHIBIT-2-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/2.1 STMARY-VC-EXHIBIT-1-OLD.png
/1. If visitors ask when the glaciers will be gone:/2.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/2.3 STMARY-VC-EXHIBIT-2-OLD.png
/1. If visitors ask when the glaciers will be gone:/2.4 STMARY-VC-EXHIBIT-2-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/3.1 STMARY-VC-EXHIBIT-1-OLD.png
/1. If visitors ask when the glaciers will be gone:/3.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/3.3 STMARY-VC-EXHIBIT-2-OLD.png
/1. If visitors ask when the glaciers will be gone:/3.4 STMARY-VC-EXHIBIT-2-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/4.1 STMARY-VC-EXHIBIT-1-OLD.png
/1. If visitors ask when the glaciers will be gone:/4.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/4.3 STMARY-VC-EXHIBIT-2-OLD.png
/1. If visitors ask when the glaciers will be gone:/4.4 STMARY-VC-EXHIBIT-2-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/5.1 STMARY-VC-EXHIBIT-1-OLD.png
/1. If visitors ask when the glaciers will be gone:/5.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/5.3 STMARY-VC-EXHIBIT-2-OLD.png
/1. If visitors ask when the glaciers will be gone:/5.4 STMARY-VC-EXHIBIT-2-UPDATED.png

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Fri Jun 14 2019 11:49:40 GMT-0600 (MDT)
To:	Marc Neidig <marc_neidig@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>
CC:	William Hayden <bill_hayden@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>
Subject:	If visitors ask when the glaciers will be gone: STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-

Attachments: UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

If visitors ask when the glaciers will be gone:
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Background on previously used prediction dates:
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STMARY-VC-EXHIBIT-1-OLD.png

STMARY-VC-EXHIBIT-1-UPDATED.png
STMARY-VC-EXHIBIT-2-OLD.png
STMARY-VC-EXHIBIT-2-UPDATED.png

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Fri Jun 14 2019 11:57:02 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

Thanks for pulling this together.

On Fri, Jun 14, 2019 at 11:50 AM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> **If visitors ask when the glaciers will be gone:**
> *Data show that in 1966, the park had 35 named glaciers large enough to be considered active. By 2015, only 26 named glaciers remained in that category. The average area reduction was 39 percent, though some lost as much as 85 percent. This trend of glacier retreat is expected to continue as*

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STMARY-VC-EXHIBIT-1-OLD.png
STMARY-VC-EXHIBIT-1-UPDATED.png

STMARY-VC-EXHIBIT-2-OLD.png

STMARY-VC-EXHIBIT-2-UPDATED.png

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Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Mckeon, Lisa" <lisa_mckeon@usgs.gov>

From:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Sent:	Mon Jun 17 2019 12:51:33 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

Nice work Daniel. Thanks for your efforts to clarify all of this and recreate the timeline of information delivery.

Lisa

Lisa McKeon
USGS - Glacier Field Station
PO Box 169
West Glacier MT 59936
406/888-7923 wk

406/253-3223 mobile
lisa_mckeon@usgs.gov

On Fri, Jun 14, 2019 at 11:50 AM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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STMARY-VC-EXHIBIT-1-OLD.png

STMARY-VC-EXHIBIT-1-UPDATED.png
STMARY-VC-EXHIBIT-2-OLD.png
STMARY-VC-EXHIBIT-2-UPDATED.png

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon Jun 24 2019 14:41:26 GMT-0600 (MDT)
To:	Deborah Smith <debby_smith@nps.gov>
Subject:	Fwd: If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

---------- Forwarded message ---------
From: **Lombardi, Daniel** <daniel_lombardi@nps.gov>
Date: Fri, Jun 14, 2019 at 11:49 AM
Subject: If visitors ask when the glaciers will be gone:
To: Marc Neidig <marc_neidig@nps.gov>, Alley, Lauren <lauren_alley@nps.gov>
Cc: William Hayden <bill_hayden@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tracy

Ammerman <tracy_ammerman@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>

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STMARY-VC-EXHIBIT-1-OLD.png

STMARY-VC-EXHIBIT-1-UPDATED.png
STMARY-VC-EXHIBIT-2-OLD.png
STMARY-VC-EXHIBIT-2-UPDATED.png

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Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Mon Jun 24 2019 17:33:48 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

Thanks!

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

I am a *proud* graduate of the GOAL Leadership Academy. Ask me about the program!

On Mon, Jun 24, 2019 at 2:42 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

---------- Forwarded message ---------
From: **Lombardi, Daniel** <daniel_lombardi@nps.gov>
Date: Fri, Jun 14, 2019 at 11:49 AM
Subject: If visitors ask when the glaciers will be gone:
To: Marc Neidig <marc_neidig@nps.gov>, Alley, Lauren <lauren_alley@nps.gov>
Cc: William Hayden <bill_hayden@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>

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STMARY-VC-EXHIBIT-1-UPDATED.png
STMARY-VC-EXHIBIT-2-OLD.png
STMARY-VC-EXHIBIT-2-UPDATED.png

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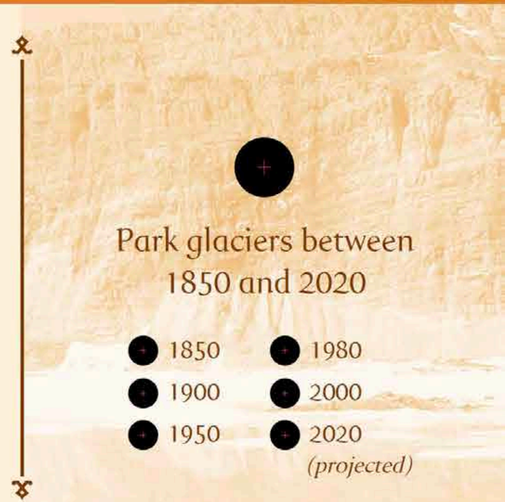
Daniel Lombardi

Visual Information Specialist
Glacier National Park
406-888-7933

GOODBYE TO THE GLACIERS

The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. They are now rapidly shrinking due to human-caused climate change. Computer models indicate the glaciers will all be gone by the year 2020.

Glacier National Park was named for the sculpting actions of the Pleistocene glaciers that covered this landscape 12,000 to 130,000 years ago.



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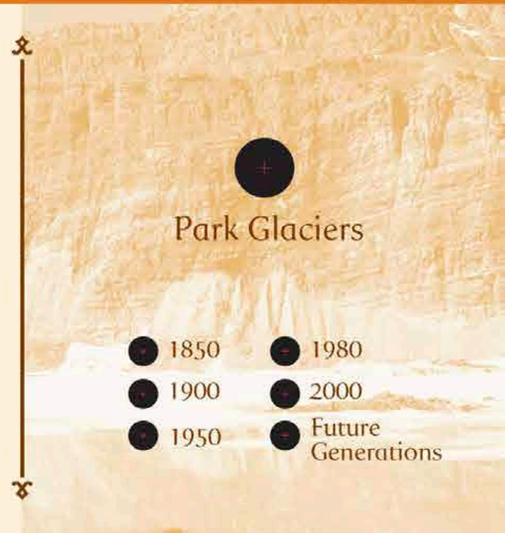
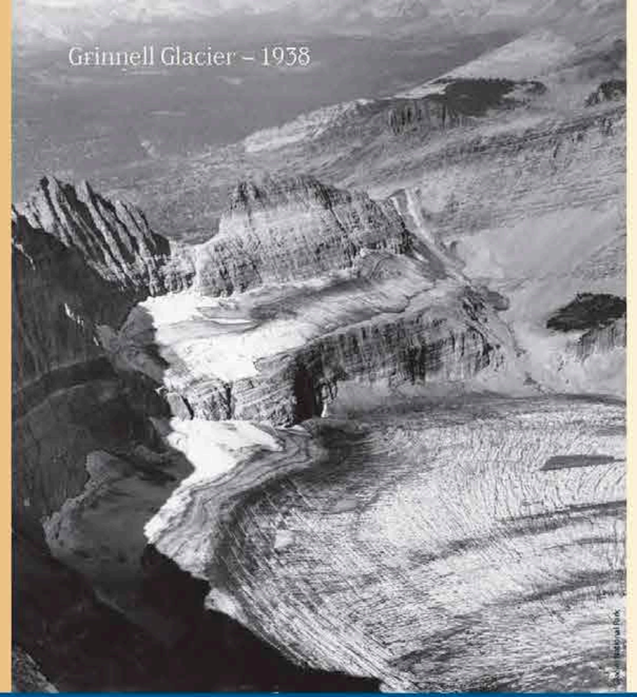
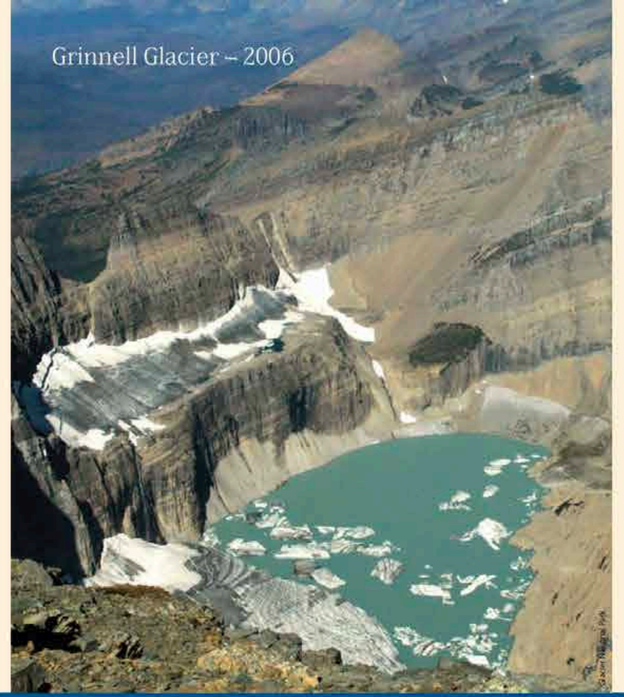


Glaciers are moving masses of ice. The glaciers that shaped the park were massive. During the pleistocene—12,000–130,000 years ago—the glaciers covering this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

In 1850 there were 150 glaciers in the park; in 2010 the number decreased to 25. Current climate models suggest that all of the glaciers in Glacier National Park will be gone by 2020.

Grinnell Glacier, located high in the Many Glacier valley, has significantly retreated in recent decades.

GLACIERS ON THE MOVE

Glaciers are moving masses of ice. During the Pleistocene—12,000–130,000 years ago—the massive glaciers shaping this landscape were thousands of feet thick.

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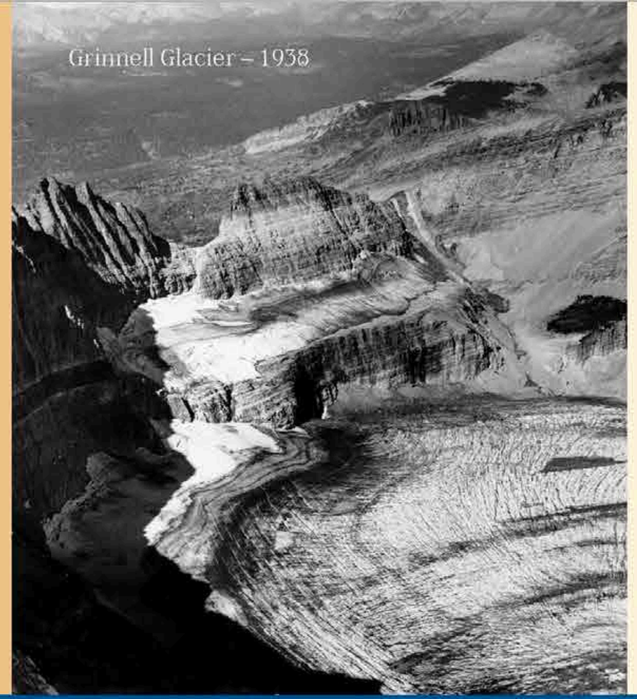

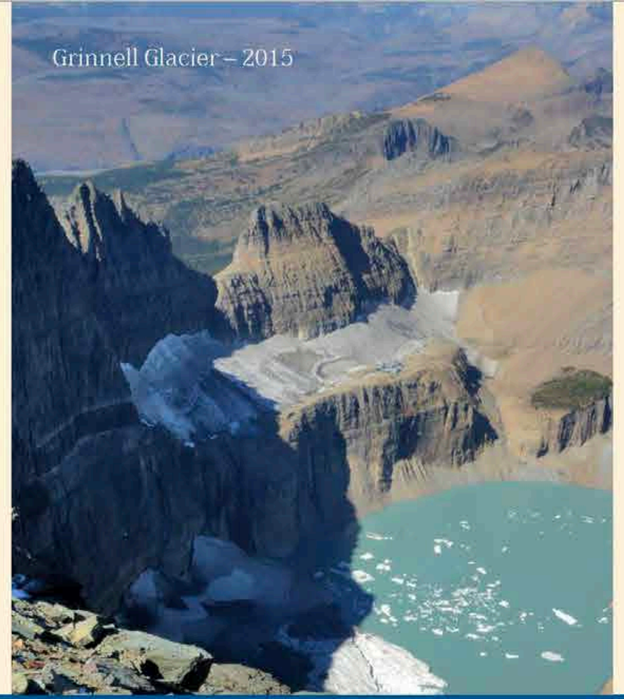

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In 1850 there were about 150 glaciers in the park. In 2015, only 26 named glaciers remained in the park.

Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking. Grinnell Glacier, located high in the Many Glacier Valley, has lost 45% of its area in recent decades.

GLACIERS ON THE MOVE

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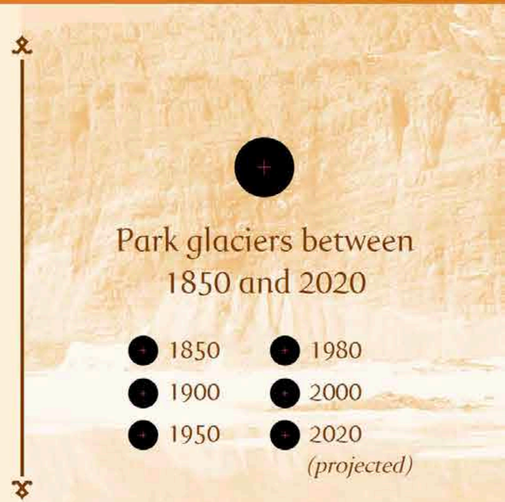

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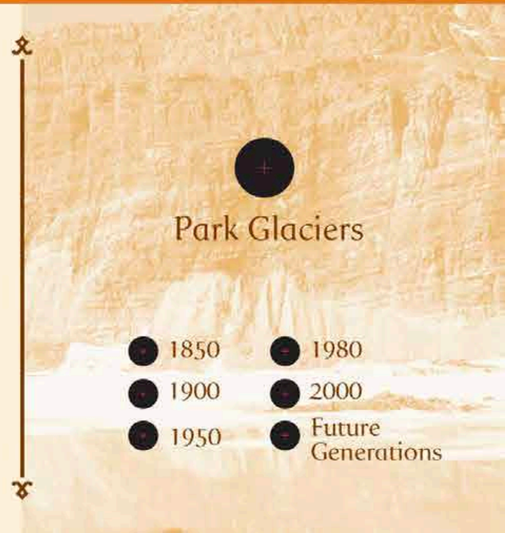

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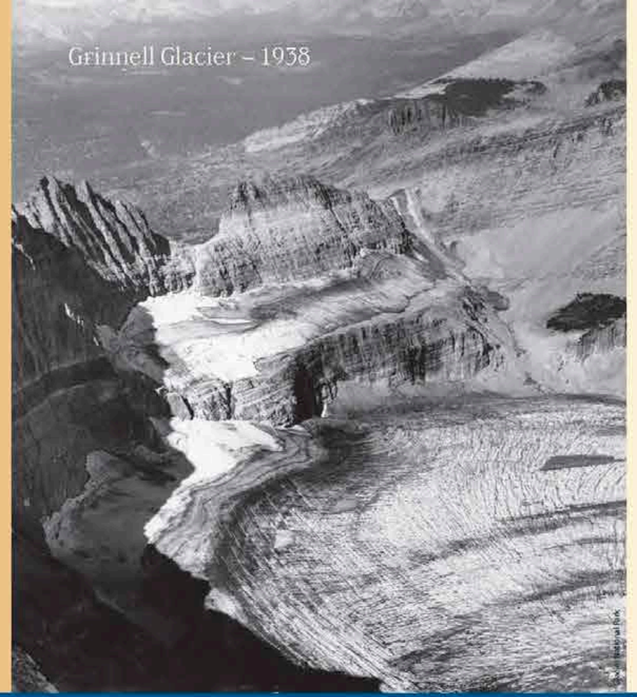

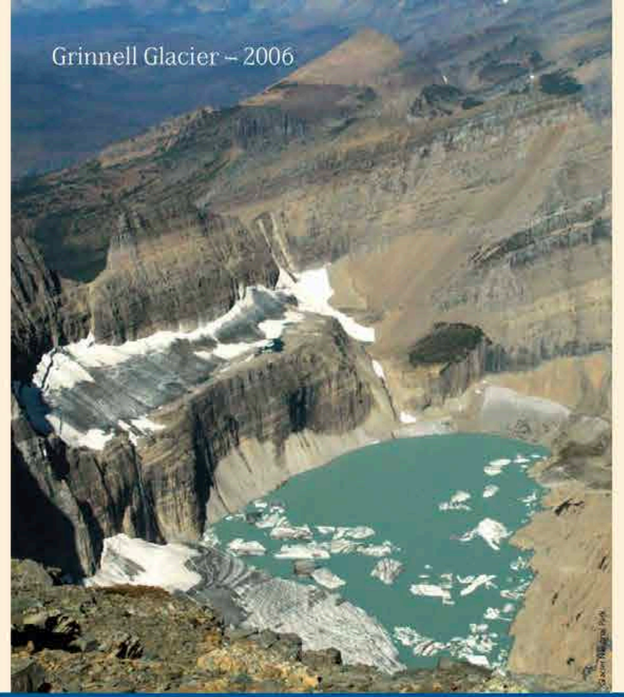

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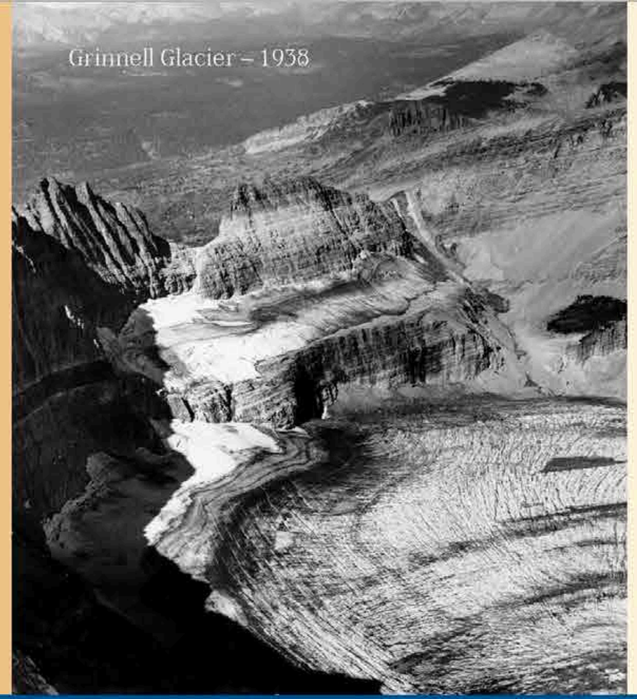

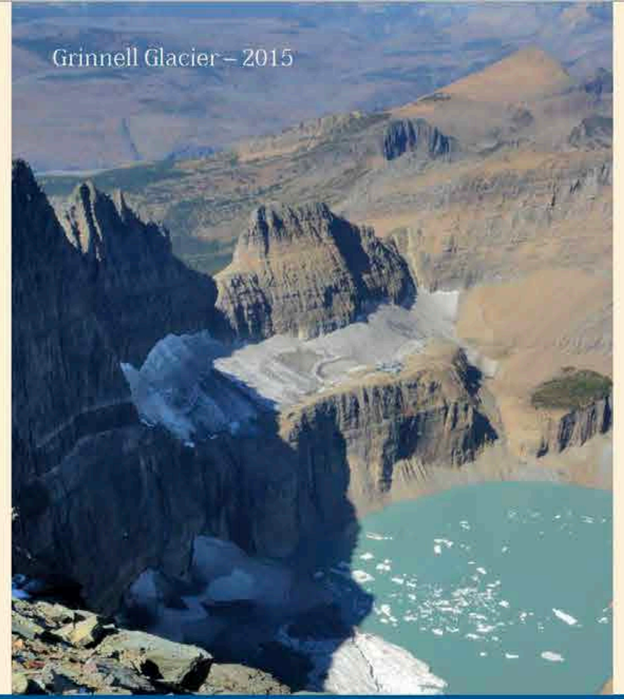

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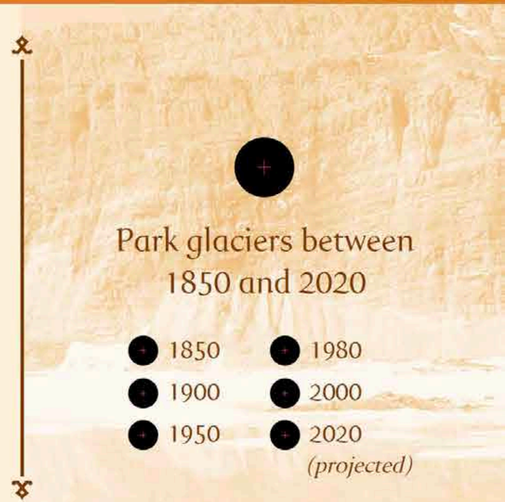

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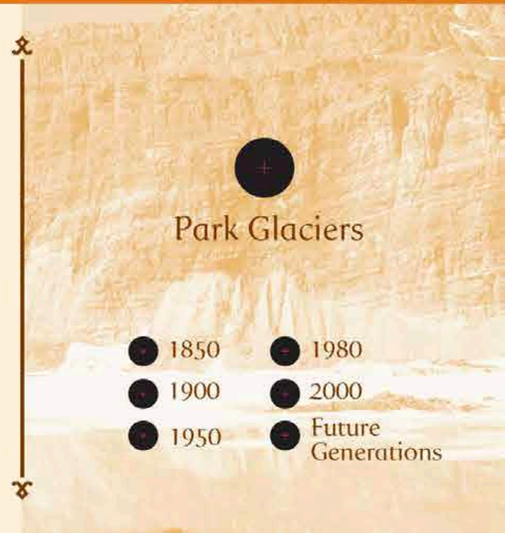

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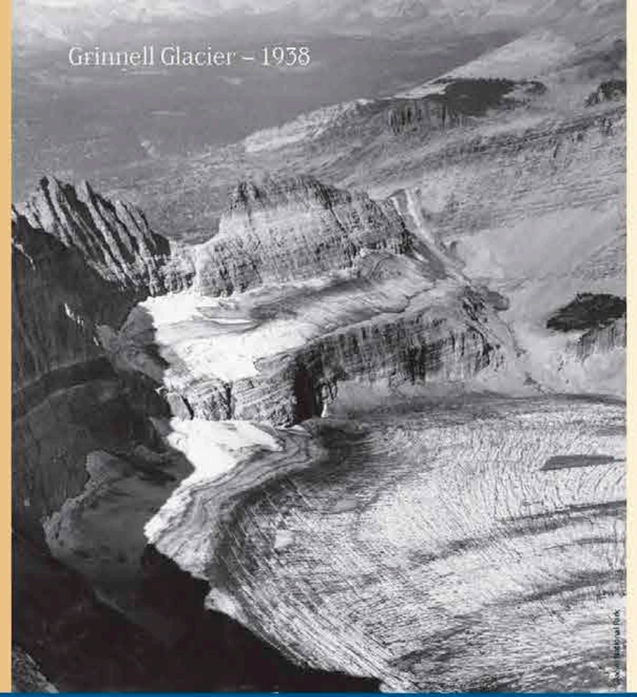

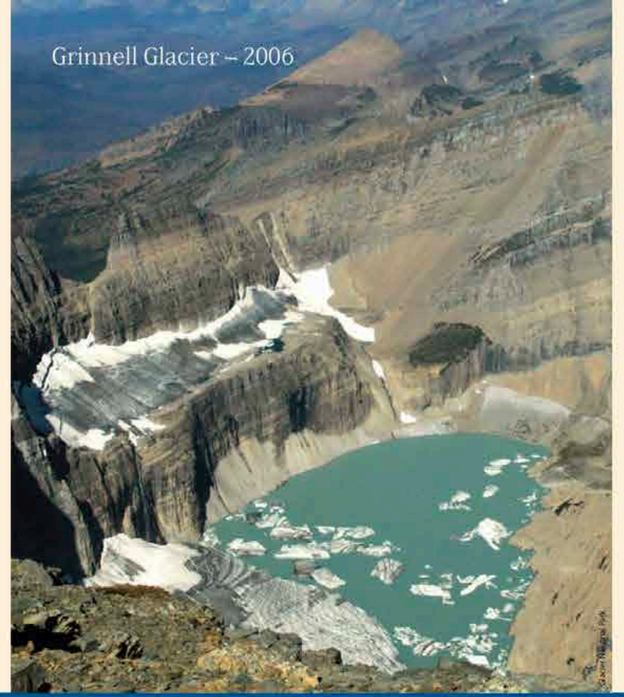

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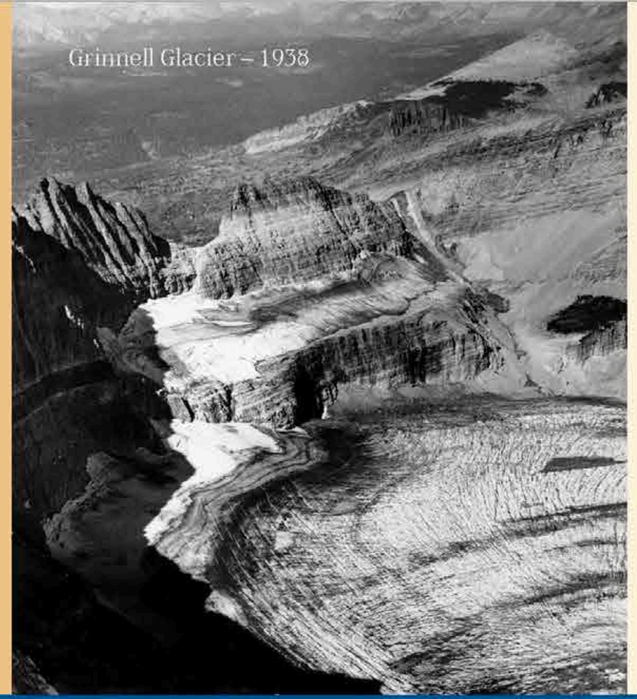

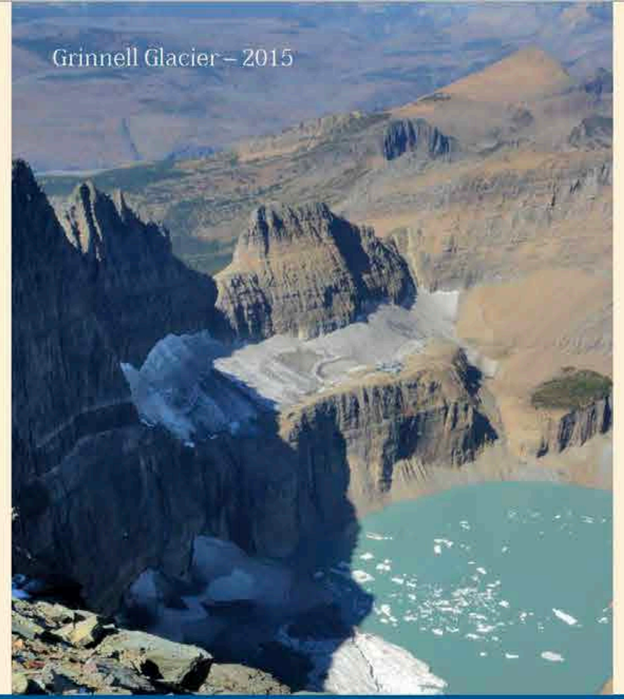

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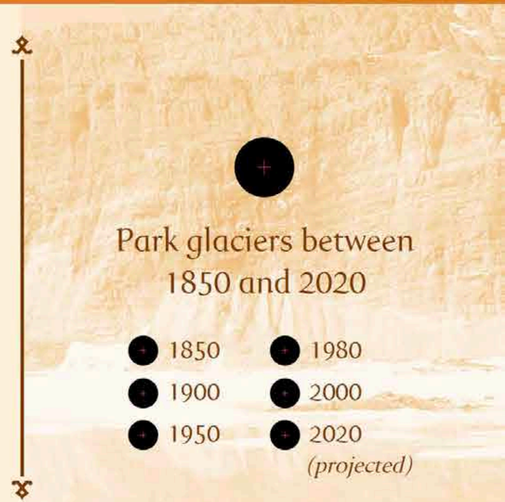

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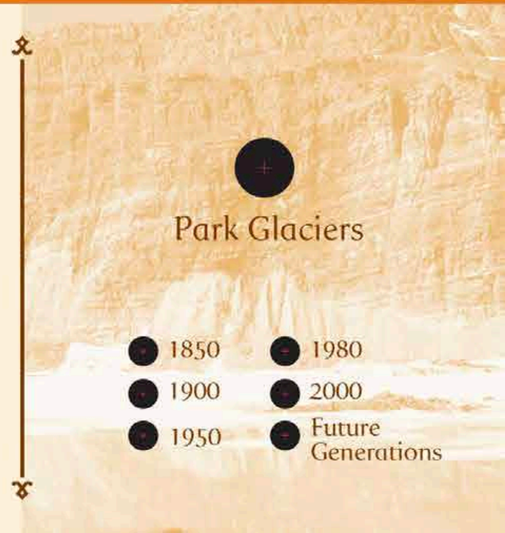

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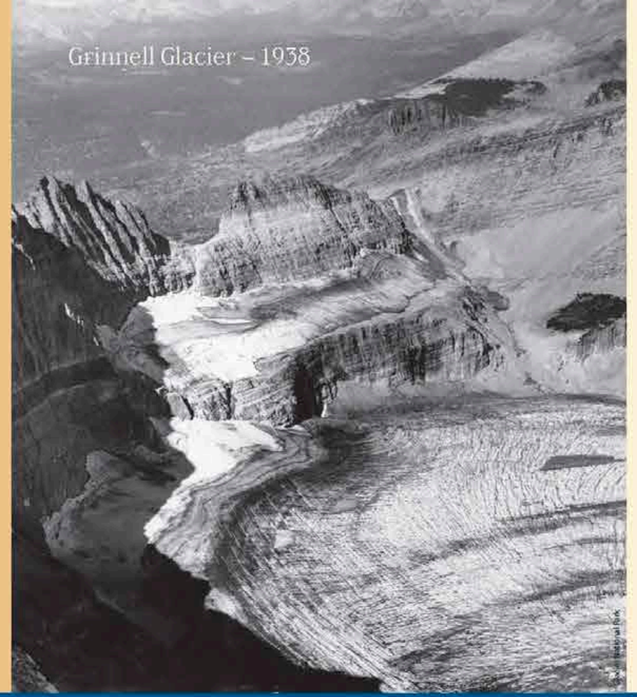

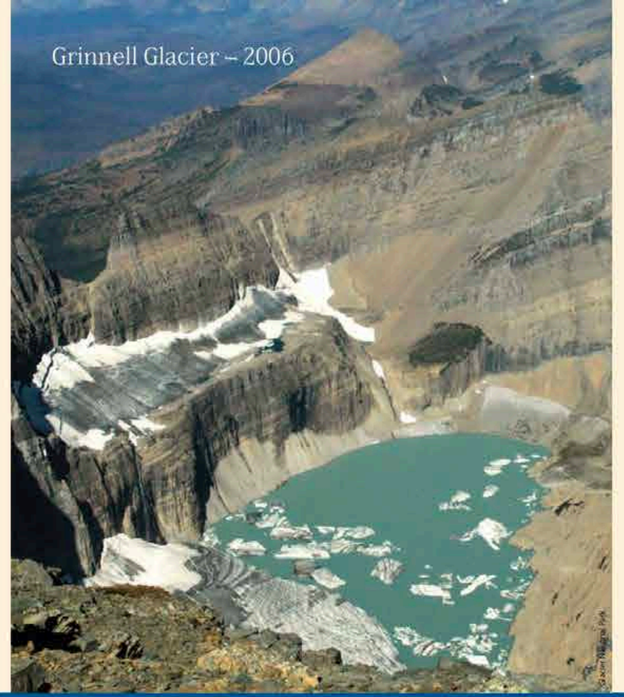

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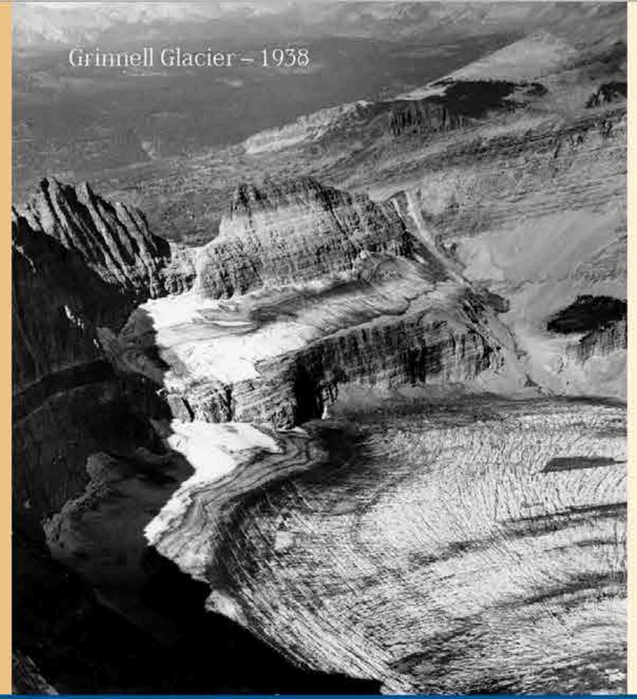

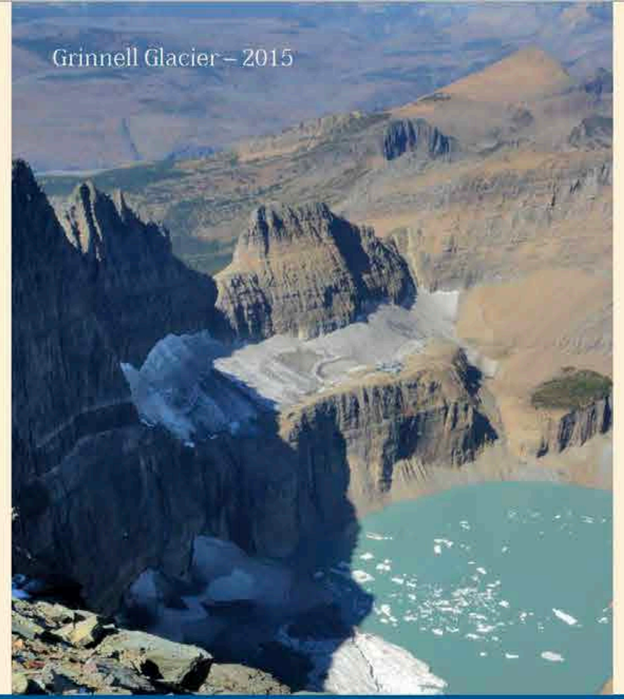

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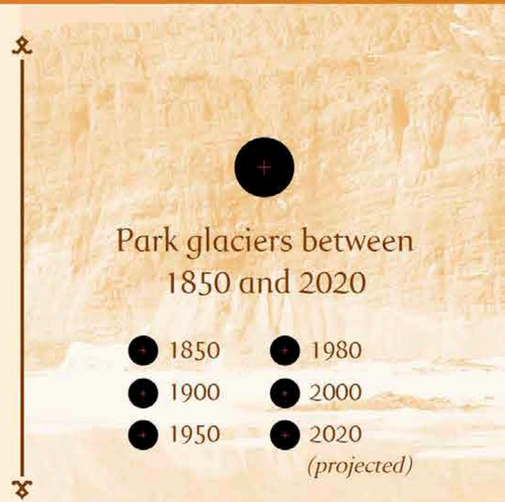

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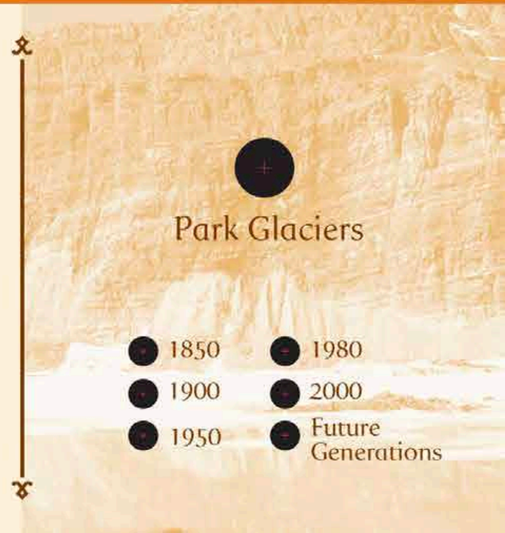

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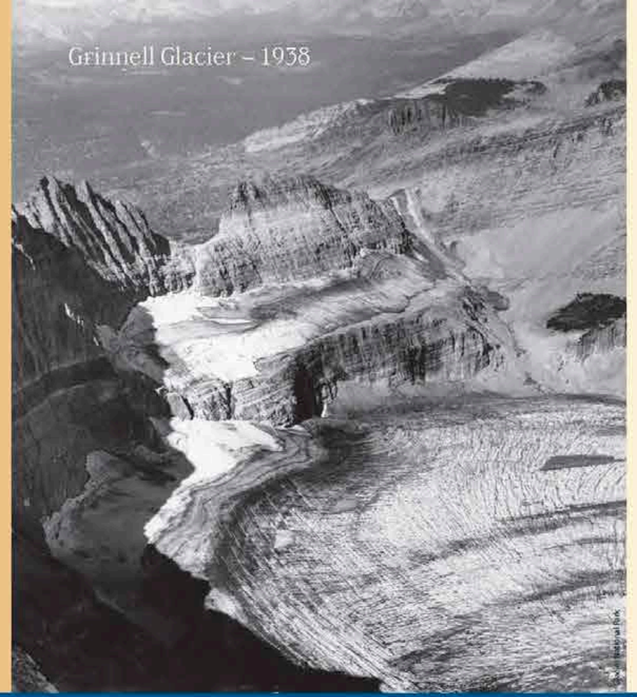

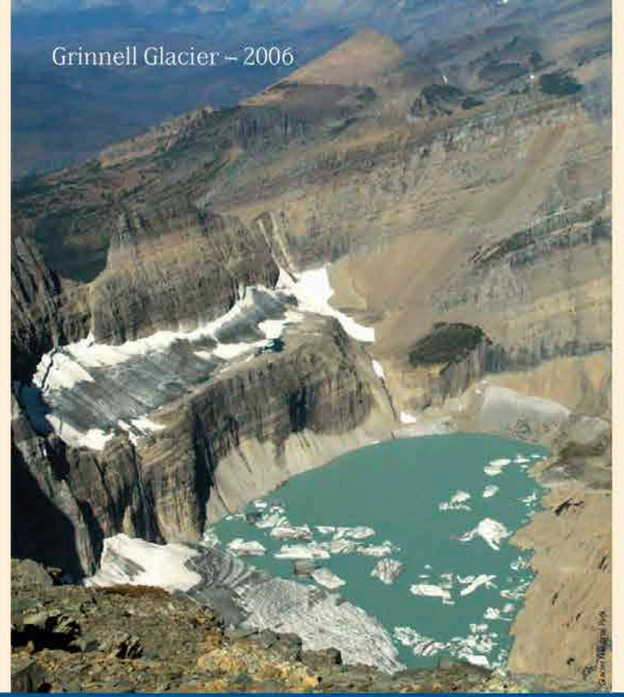

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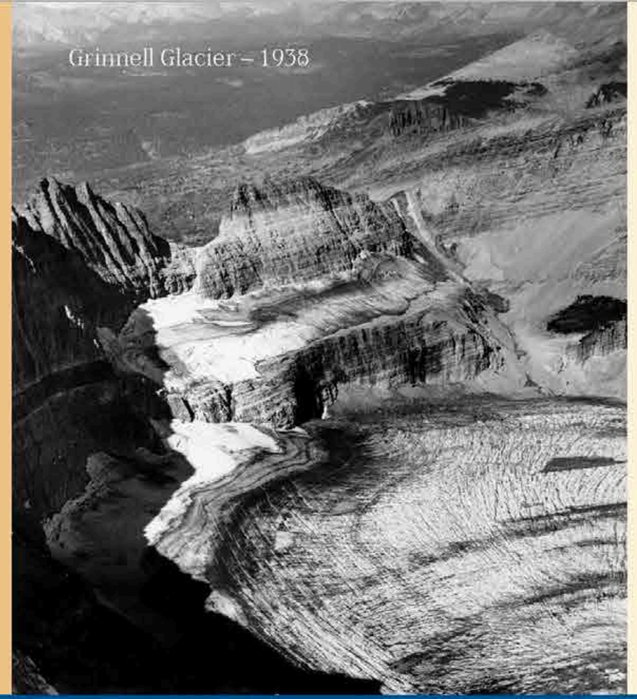

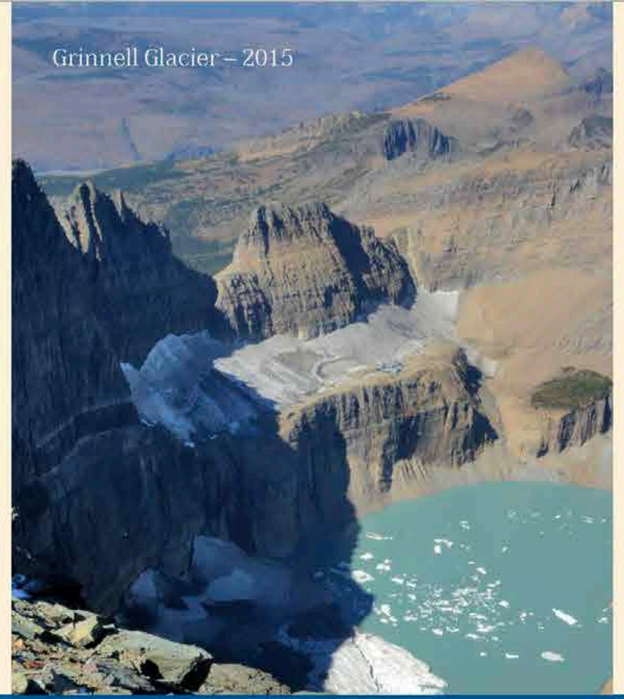

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Conversation Contents

Wayside Exhibit Projects

Attachments:

/2. Wayside Exhibit Projects/1.1 waysides for jeff.docx

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Tue Jun 11 2019 13:33:22 GMT-0600 (MDT)
To:	Connie Stahr <connie_stahr@nps.gov>
CC:	Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Wayside Exhibit Projects
Attachments:	waysides for jeff.docx

Attached is a brief outline of ongoing and upcoming exhibit projects around the park. I have listed the PMIS numbers for the ones that are included in SCC proposals.

This list does not include all exhibits and does not include interior exhibits in the visitor centers. That list will take more time to generate.

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Wed Jun 19 2019 14:35:20 GMT-0600 (MDT)
To:	"Hayden, William" <bill_hayden@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: Wayside Exhibit Projects

Thanks, Bill!

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
~~~~~~~~~~~~~~~~~~~~~~~~~~

406-888-7930

On Tue, Jun 11, 2019 at 1:33 PM Hayden, William <bill_hayden@nps.gov> wrote:

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Rehabilitate Many Glacier Waysides – 11 wayside exhibits

PMIS Project 238642 – scheduled for 2020

In 2016 we submitted a PMIS proposal to update and repair the Many Glacier Wayside Exhibits. They were installed is 2014 and 2015. This is a cyclic maintenance proposal. In addition to repair and rehab of bases the content will be reviewed for needed resource and safety updates. The exhibits cover a broad range of subjects from hydrological features, wildlife habitat, cultural history and visitation patterns, and how glaciers function, their impact on the parks geography, and their rate of melting. In these exhibits there is one bit of information that should be changed regarding glaciers. A sentence states that the glaciers will be gone in our lifetime. Depending on who is reading that exhibit, we should probably change that to may be gone.

In addition to these 11 waysides there are seven exhibit panels on the accessible portion of the Swiftcurrent Nature Trail and 7 trailhead panels at the beginnings of trails. One of the exhibit panels on the Swiftcurrent Nature Trail says that Scientists predict the park's alpine glaciers will vanish in the near future.

Rehabilitate Going-to-the-Sun Road West Side Waysides – 18 wayside exhibits

PMIS Project 239034 – scheduled for 2021

In 2016 we submitted a PMIS proposal to update and repair wayside exhibits along the west side of the Going-to-The-Sun Road. This is a cyclic maintenance proposal. Bases and frames will be repaired and/or replaced and exhibit content will be reviewed and changed as needed. As in other areas the exhibits speak to a broad range of topics and are mostly site specific to the view in that particular location.

One exhibit that should probably change sooner than 2021 is just south of the lodge. It is about the 2003 Howe Ridge Fire. Although the content is correct, it does not address that there was a fire in that same location in 2018. Visitors could be left with the impression that what they are looking at is all from 2003. Some of it is and some is from 2018.

Two of the exhibits directly address glaciers but they primarily discuss the carving done by the historic glaciers and not the current smaller ones. These two exhibits talk about melting but do not include any dates.

Review of this set of exhibits will be conducted to ensure that content still contains the most recent research findings and information.

In addition to these waysides there are nine exhibit panels along the Trail of the Cedars and five trailhead panels along this portion of the Going-to-the-Sun Road.

Rehabilitate Going-to-the-Sun Road East Side Waysides – 7 wayside exhibits

PMIS Project 257141 – scheduled for 2023

In 2018 we submitted a PMIS proposal to update and repair wayside exhibits along the west side of the Going-to-The-Sun Road. This is a cyclic maintenance proposal. Bases and frames will be repaired and/or replaced and exhibit content will be reviewed and changed as needed.

As a group these exhibits have climate change messages more than other areas of the park. None of them have dates associated with them. Two of them directly address climate change and glacial retreat (Jackson Glacier Overlook). The Triple Divide and St. Mary River waysides include statements that question how a changing climate will affect the park and water availability downstream.

In addition there are trailhead panels at 5 locations.

Rehabilitate Logan Pass Waysides – 20 wayside exhibits

PMIS Project 257143 – scheduled for 2024

In 2018 we submitted a PMIS proposal to update and repair wayside exhibits along the west side of the Going-to-The-Sun Road. This is a cyclic maintenance proposal. Bases and frames will be repaired and/or replaced and exhibit content will be reviewed and changed as needed. The exhibits at Logan Pass focus on wildlife and plant adaptations to the sub-alpine environment and geologic history. Two of the exhibits at Logan Pass currently have dates for when the glaciers will be gone that are no longer consistent with recent research findings. These two panels should be changed. We should not wait until the entire project is funded to complete these revisions.

Rehabilitate North Fork Waysides – 20 wayside exhibits

PMIS Project 237853

We are currently working to revise, repair, and rehabilitate wayside exhibits in the North Fork/Camas Road area and locations in Apgar and West Glacier. This set of exhibits highlight cultural history on the west side of the park, fire history, wildlife, and recreational opportunities. To a large extent climate change messages are not included in these exhibits. We are looking to revise language that exists on the waysides in place now and we are changing some topics to make planning recreational activities easier and safer. Our fire messages will highlight recent activity in the park and make those exhibits reflect current conditions.

Two Medicine Wayside Exhibits. – 14 wayside exhibits

Within the last year we updated exhibits in the Two Medicine Valley. Exhibits on native plant uses have been designed and are awaiting tribal consultation. There is a new exhibit by the Campstore. It replaces the old exhibit about the chalet system parkwide and replaces it with an exhibit specific to the Campstore building and its history as a part of the Two Medicine Chalets. A replacement exhibit was

placed at the Two Medicine Train Depot updating the connection that trains played in the development of the park. There is an exhibit on the history of the building of the Glacier Park Lodge that replaced an older exhibit on the red buses. Once Glacier Park Inc. lost the contract for the park they were no longer associated with the red buses. Rather than remove the exhibit altogether it was replaced with an exhibit that highlighted the building of the hotel and the connection with the Great Northern. In the future a decision could be made to remove this exhibit entirely. We have not had those discussion as of yet.

There are two trailhead panels in the Two Medicine Valley.

Other Exhibits

Additional PMIS projects are in the system to rehabilitate and replace trailhead panels throughout the park…a multi year proposal, and to redo exhibits at Goat Haunt. Both projects were moved to later years in the comp plan.

This summer we are finishing work on Sun Point exhibits (12 panels), continuing work on exhibits about the Salish/Kootenai, updating LEEDs signs at the Apgar Visitor Center, a historic walking tour for HQ, and an exhibit on Mission 66 to mitigate an adverse effect on the restroom in the Apgar Campground.

There is a proposal in the system to rehabilitate the exhibits at the St. Mary Visitor Center. It is PMIS #257367. It is a multi-year Rec Fee project and was moved back in the comp plan earlier this year.

Conversation Contents

Winter Exhibits

Attachments:

/3. Winter Exhibits/1.1 IMG_9867.JPG
/3. Winter Exhibits/1.2 IMG_9865.JPG
/3. Winter Exhibits/1.3 LOGAN PASS VC EXHIBITS MAP.png

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon Jun 17 2019 08:57:52 GMT-0600 (MDT)
To:	William Hayden <bill_hayden@nps.gov>
Subject:	Winter Exhibits
Attachments:	IMG_9867.JPG IMG_9865.JPG LOGAN PASS VC EXHIBITS MAP.png

Hey Bill,

The shuttle panels from September 2018 are all up on the east side of Going-to-the-Sun Road.

At Logan Pass the triangle exhibit right out the back door of the visitor center (labled Hiking Map, LPVC, Climate Change) appears to have been left out all winter. It broke off the ground and one third broke away as well.

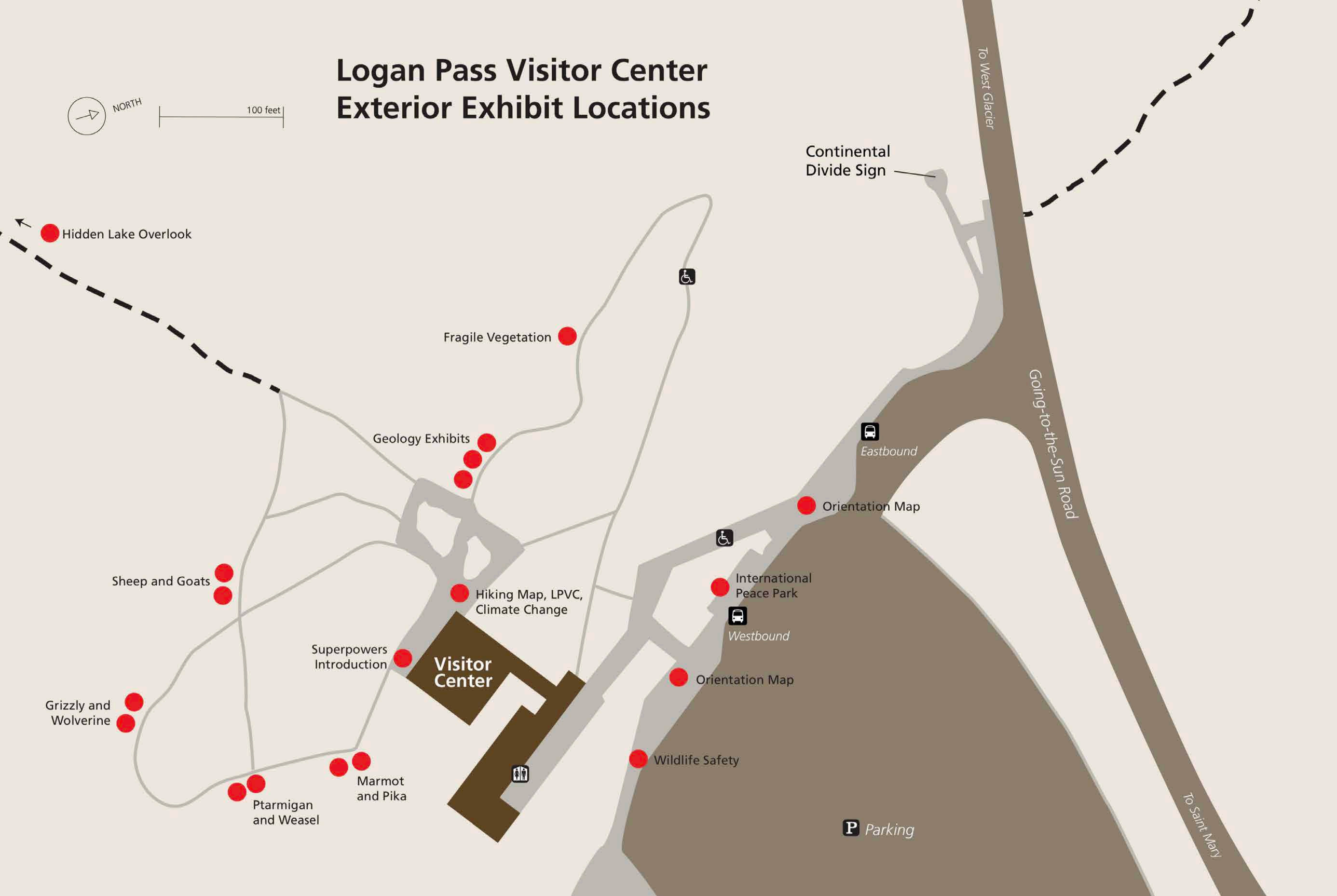
I didn't see anything else left out. I couldn't see any of the waysides inside the visitor center by looking through the windows.

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

Closed

Logan Pass Trails

Logan Pass Visitor Center Exterior Exhibit Locations



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Re: Exhibit text and/or photos ASAP?

Attachments:

/4. Re: Exhibit text and/or photos ASAP?/1.1 GL-07-400rev2.pdf
/4. Re: Exhibit text and/or photos ASAP?/1.2 GL-07-400 May 2019 Revisions.pdf
/4. Re: Exhibit text and/or photos ASAP?/1.3 GL-06-300 updated MAY 2019.pdf
/4. Re: Exhibit text and/or photos ASAP?/1.4 GL-06-300rev1.pdf
/4. Re: Exhibit text and/or photos ASAP?/2.1 GL-07-400rev2.pdf
/4. Re: Exhibit text and/or photos ASAP?/2.2 GL-07-400 May 2019 Revisions.pdf
/4. Re: Exhibit text and/or photos ASAP?/2.3 GL-06-300 updated MAY 2019.pdf
/4. Re: Exhibit text and/or photos ASAP?/2.4 GL-06-300rev1.pdf

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Sat Jun 08 2019 16:20:37 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, "Mensch, D" <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Here are some attachments and some background.

The exhibits in the St. Mary Visitor Center were probably installed in 2010. There had been several planning and design meetings with Harpers Ferry Center personnel in the several years previous. Mark Wagner was the lead on the exhibit redesigns. Sheri Forbes was the Chief of Interpretation. I was actually not involved in any aspect of the project or meetings from start to finish, so my memory on the exact dates is fuzzy. My guess on the year is based on the final planning document from the fabricator of the exhibits. The planning and design most surely happened much prior to that date. Mark Wagner may know more specifics.

In any case the exhibits that deal with glacial retreat were based on the USGS information that was available at that time. Since then their research has continued and evolved to include a more refined picture of glaciers in the park. Like much of scientific research, there are often not concrete black and white answers to basic questions, and that is often hard for some people to grapple with.

In the late summer, or fall, of 2017 staff from the USGS informed us, the media staff, that there were dates in the exhibits near the relief map at St. Mary that were not consistent with current research and asked that we change them. We were unable to do that for the 2018 season. At the end of the season we removed the exhibits and made changes to the original files. Those changes went through review by NPS and USGS staff and our sign shop was able to fabricate them and have them installed just prior to the opening of the Visitor Center this spring. Attached

you should find the new exhibits and the former exhibits as PDF files.

There are also exhibits at the Apgar and St. Mary Visitor Center plazas, outside, that have dates that need changing. Those exhibits date from 2007. There are two exhibits that I know of at Logan Pass that likewise have these dates and should be changed out. In 2018 two new glacier exhibits replaced the one exhibit at Jackson Glacier Overlook. The old one had the 2030 date on it as well. It also contained images from the computer projection model, that was based on USGS work published in the early 2000s, I think 2003. This oldexhibit was designed in 2006 in coordination with Leigh Welling, who was in charge of the Crown of the Continent Research Learning Center at the time. I remember the date because I worked on refining her files while I was in Seattle that entire summer. She went from Glacier to a position in Colorado for the Natural Resources Division, where she dealt specifically with climate change issues.

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Daniel/Tracy feel free to provide any details or updates that I may have missed or gotten wrong.

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> Sent from my iPad

--

Bill Hayden
Interpretive Specialist

Glacier National Park
West Glacier, MT 59936
406-888-7927

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Sat Jun 08 2019 16:44:54 GMT-0600 (MDT)
To:	Connie Stahr <connie_stahr@nps.gov>
Subject:	Fwd: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Hey Connie, Bill asked me to forward this to you because he already closed his computer and had forgot to include you.

---------- Forwarded message ---------
From: **Hayden, William** <bill_hayden@nps.gov>
Date: Sat, Jun 8, 2019 at 4:20 PM
Subject: Re: Exhibit text and/or photos ASAP?
To: Lauren Alley <lauren_alley@nps.gov>
Cc: Lee Rademaker <lee_rademaker@nps.gov>, Mensch, D <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>

Here are some attachments and some background.

The exhibits in the St. Mary Visitor Center were probably installed in 2010. There had been several planning and design meetings with Harpers Ferry Center personnel in the several years previous. Mark Wagner was the lead on the exhibit redesigns. Sheri Forbes was the Chief of Interpretation. I was actually not involved in any aspect of the project or meetings from start to finish, so my memory on the exact dates is fuzzy. My guess on the year is based on the final planning document from the fabricator of the exhibits. The planning and design most surely happened much prior to that date. Mark Wagner may know more specifics.

In any case the exhibits that deal with glacial retreat were based on the USGS information that was available at that time. Since then their research has continued and evolved to include a more refined picture of glaciers in the park. Like much of scientific research, there are often not concrete black and white answers to basic questions, and that is often hard for some people to grapple with.

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Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Stahr, Connie" <connie_stahr@nps.gov>

From:	"Stahr, Connie" <connie_stahr@nps.gov>
Sent:	Mon Jun 10 2019 09:24:22 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: Exhibit text and/or photos ASAP?

Thank you Daniel!

Connie Stahr
Executive Assistant
Office of the Superintendent
Glacier National Park
P.O. Box 128
West Glacier, MT 59936
406-888-7901 Phone
406-888-7904 Fax

On Sat, Jun 8, 2019 at 4:45 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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Daniel Lombardi
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GOODBYE TO THE GLACIERS

The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. They are now rapidly shrinking due to human-caused climate change. Computer models indicate the glaciers will all be gone by the year 2020.

Glacier National Park was named for the sculpting actions of the Pleistocene glaciers that covered this landscape 12,000 to 130,000 years ago.

Park glaciers between 1850 and 2020

- 1850
- 1900
- 1950
- 1980
- 2000
- 2020 *(projected)*

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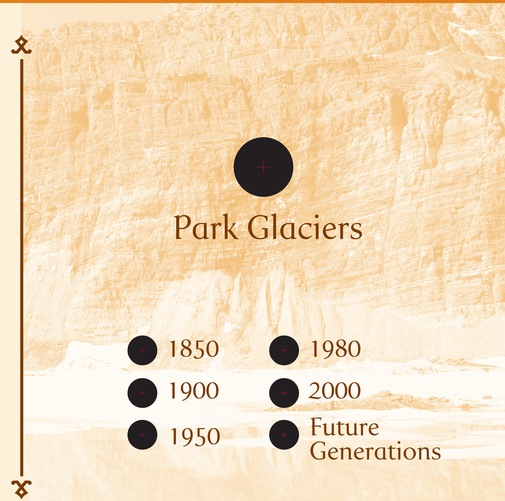
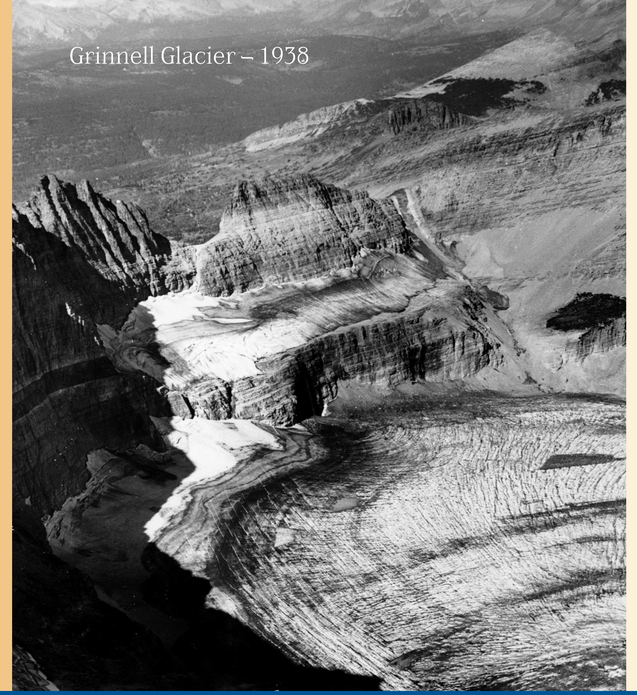
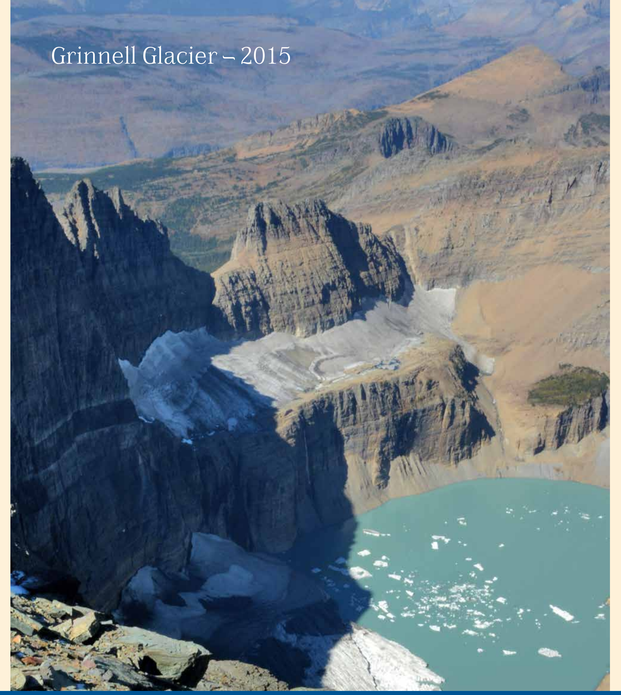


Glaciers are moving masses of ice. During the Pleistocene—12,000–130,000 years ago—the massive glaciers shaping this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

In 1850 there were about 150 glaciers in the park. In 2015, only 26 named glaciers remained in the park.

Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking. Grinnell Glacier, located high in the Many Glacier Valley, has lost 45% of its area in recent decades.

GLACIERS ON THE MOVE

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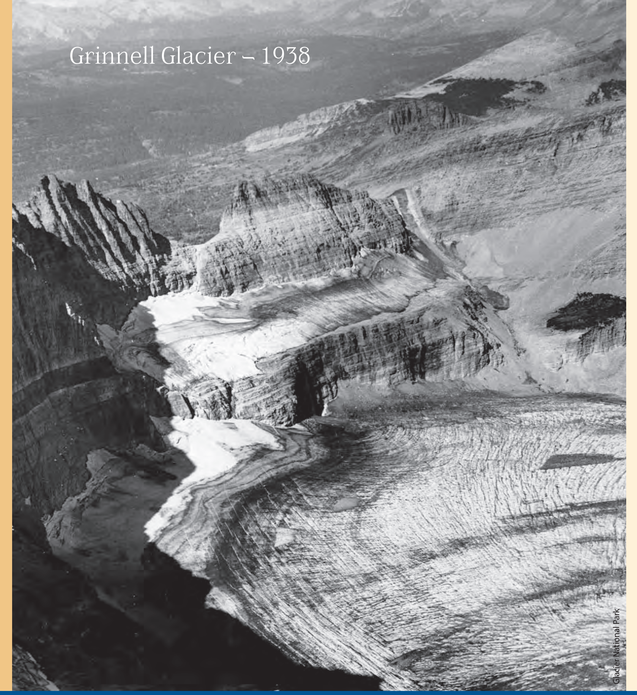

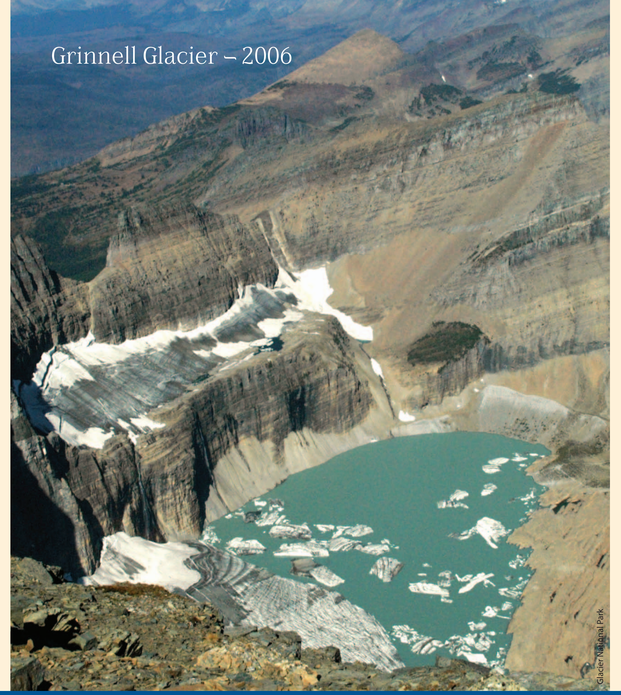

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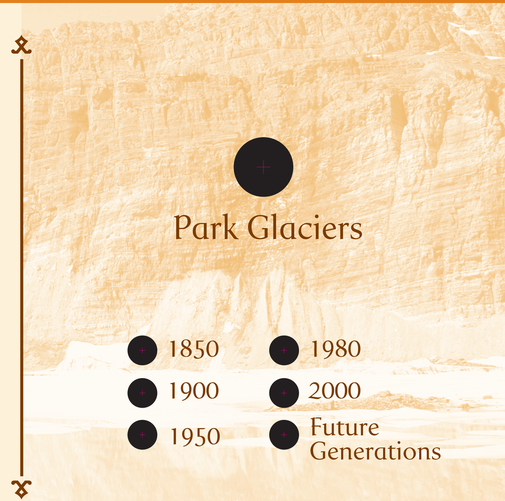

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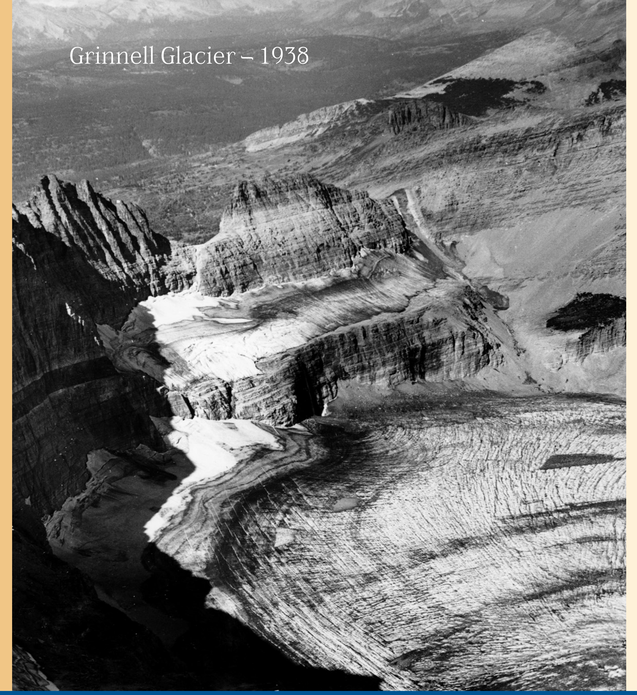

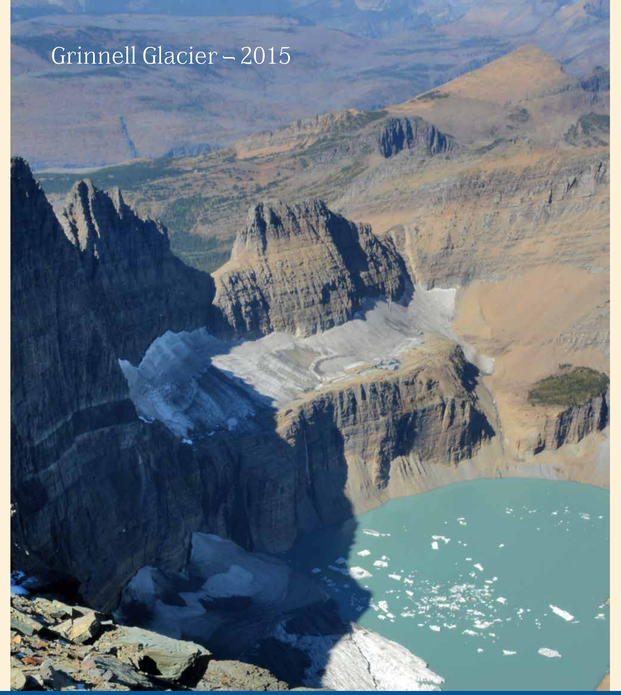

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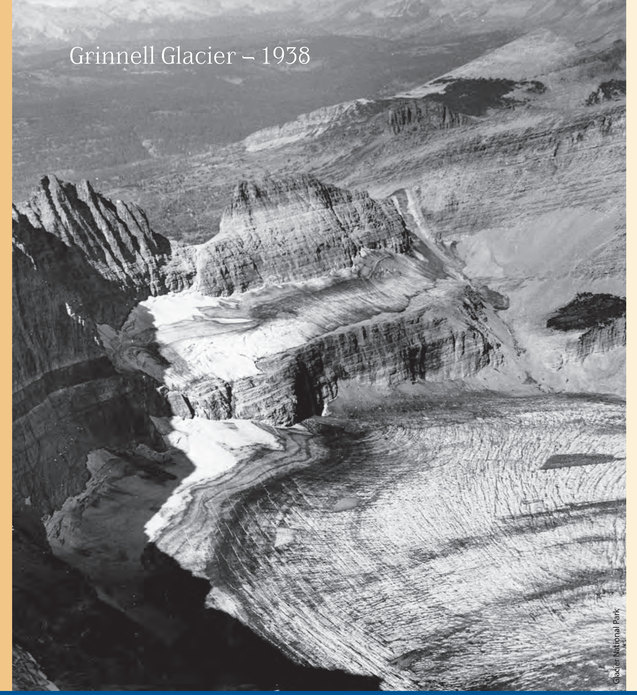

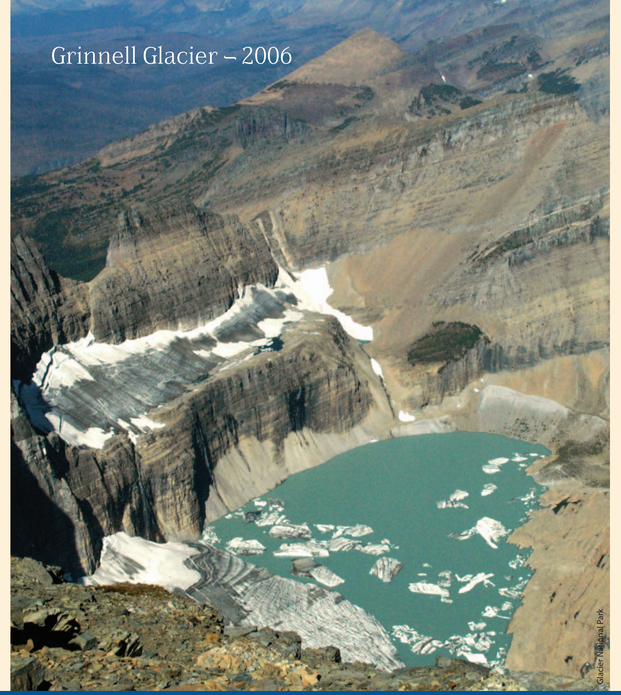

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GLACIERS ON THE MOVE

Conversation Contents

Fwd: Media Inquiry: [EXTERNAL] Is this true?

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Thu Jun 06 2019 14:56:05 GMT-0600 (MDT)
To:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

FYI

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930

---------- Forwarded message ---------
From: **Ammerman, Tracy** <tracy_ammerman@nps.gov>
Date: Thu, Jun 6, 2019 at 1:31 PM
Subject: Re: Media Inquiry: [EXTERNAL] Is this true?
To: Lauren Alley <lauren_alley@nps.gov>

Lauren,

Yes, we are indeed updating our interpretive information/exhibits based on emerging information from USGS. There was nothing covert or sneaky about it, but simply an effort to try to have more accurate information in place before the SMVC opened to the public this year. The park's position (based on scientific evidence) is still that our glaciers are shrinking and disappearing and that there is typically a net loss of mass "at the end of the year." The prediction that they would be gone by 2020 appears to have been an inaccurate estimate based on the models used at that time, but there is absolutely no disagreement in the scientific community that they will disappear in the not-too-distant future. GLAC is removing specific dates and using more general language, as we (and USGS) have realized that although the trend is evident, citing a specific date was perhaps presumptive.

I hope this helps. I am happy to chat with you more if you'd like. Of course, discussion with Dan Fagre and/or Caitlyn Florentine might be useful, as well.

Tracy
~~~~~~~~~~~~~~~~~~~~~~~~~~

~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930

On Thu, Jun 6, 2019 at 1:13 PM Lauren Alley <lauren_alley@nps.gov> wrote:

> Tracy- do you have anything to add? Assume that we are updating interpretive material and have been for several years to reflect latest USGS models.
>
> Sent from my iPhone
>
> Begin forwarded message:
>
> **From:** "Kupper, Kathy" <kathy_kupper@nps.gov>
> **Date:** June 6, 2019 at 12:11:09 PM MDT
> **To:** "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>
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> Hi Lauren,
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> DOI received a media inquiry regarding the following article. Can you please let us know if the info in it is correct and/or any related background?
> https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc
>
> Thank you,
> Kathy
>
> Kathy Kupper
> Public Affairs Specialist
> Office of Communications
> National Park Service
> (202)513-7263
> www.nps.gov
>
> The National Park Service cares for special places saved by the American people so that all may experience our heritage.
>
> EXPERIENCE YOUR AMERICA ®
~~~~~~~~~~~~~~~~~~~~~~~~~

"Carolin, Tara" <tara_carolin@nps.gov>

From:	"Carolin, Tara" <tara_carolin@nps.gov>
Sent:	Fri Jun 07 2019 13:38:42 GMT-0600 (MDT)
To:	Melissa Sladek <melissa_sladek@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

Tara Carolin, Director
Crown of the Continent Research Learning Center
Glacier National Park
406-888-7863
406-888-7903 (fax)
https://www.nps.gov/rlc/crown

Research Learning Centers increase the effectiveness and communication of science in national parks.

---------- Forwarded message ---------
From: **Alley, Lauren** <lauren_alley@nps.gov>
Date: Thu, Jun 6, 2019 at 6:08 PM
Subject: Re: Media Inquiry: [EXTERNAL] Is this true?
To: Kupper, Kathy <kathy_kupper@nps.gov>
Cc: Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>, Beldin, Sarah <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov>

Kathy/all,

Please see below for some context. I'm copying USGS public affairs for the Northern Rockies (Sarah Beldin) and the lead USGS scientist (Dan Fagre) on this response in case you or DOI have any follow up questions for us.

Cheers,

Lauren

The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.

USGS regularly publicizes their research efforts. The National Park Service does not typically issue press releases for new interpretive displays or park signage.

A paper published in 2003 predicted that the glaciers in Glacier National Park would be gone by 2030, based on modeling that the glaciers would continue to melt at the same rate that they had over the previous decades.

Further research in the late 2000s revealed specific glaciers were melting even faster than the

rate used in the 2003 model, which began predictions that at least some of the glaciers may be gone as early as 2020. (See page 80 of the linked article.)

Research on the glaciers has continued. In the last several years, USGS has released peer reviewed research on glacial retreat that provide greater accuracy than was available early on in the research project, including improved satellite images and a greater understanding of how site specific conditions affect glacier size and melt rate. The research shows variability in the rate at which individual glaciers are melting though the overall declining trend continues. Recent data show reductions in size range from 9%-96%, averaging a 68% reduction in glacial area overall.

The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.

In the past three years, the park has used the following statement when responding to the multiple media requests it receives about glacial retreat:

"There are currently 26 glaciers in the park. Scientific models project that many will no longer meet the size criteria used to define a glacier sometime between 2030 and 2080."

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

On Thu, Jun 6, 2019 at 12:11 PM Kupper, Kathy <kathy_kupper@nps.gov> wrote:

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>
> The National Park Service cares for special places saved by the American people so that all may experience our heritage.
>
> EXPERIENCE YOUR AMERICA ®

Conversation Contents

That was quick...

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu Jun 06 2019 13:34:15 GMT-0600 (MDT)
To:	Deborah Smith <debby_smith@nps.gov>, Lee Rademaker <lee_rademaker@nps.gov>, "Sine, Diane" <diane_sine@nps.gov>, William Hayden <bill_hayden@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Melissa Sladek <melissa_sladek@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>
Subject:	That was quick...

The new St. Mary exhibits were noticed:

https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Tomlin, Teagan" <teagan_tomlin@nps.gov>

From:	"Tomlin, Teagan" <teagan_tomlin@nps.gov>
Sent:	Thu Jun 06 2019 14:01:01 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: That was quick...

Have you read the comments?

Teagan Tomlin
Visitor Services Assistant
Glacier National Park
406-888-7931

On Thu, Jun 6, 2019 at 1:34 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> The new St. Mary exhibits were noticed:
>
> https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/
>
> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
> 406-888-7933

"Sladek, Melissa" <melissa_sladek@nps.gov>

From:	"Sladek, Melissa" <melissa_sladek@nps.gov>
Sent:	Thu Jun 06 2019 14:29:25 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Deborah Smith <debby_smith@nps.gov>, Lee Rademaker <lee_rademaker@nps.gov>, "Sine, Diane" <diane_sine@nps.gov>, William Hayden <bill_hayden@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>
Subject:	Re: That was quick...

You guys are so sneaky! Yikes, what an article!

Melissa Sladek
Science Communication Specialist
Crown of the Continent Research Learning Center
Glacier National Park
P.O. Box 128
West Glacier, MT 59936
406-888-7894

On Thu, Jun 6, 2019 at 1:34 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> The new St. Mary exhibits were noticed:
>
> https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/
>
> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park

> 406-888-7933

"Sine, Diane" <diane_sine@nps.gov>

From:	"Sine, Diane" <diane_sine@nps.gov>
Sent:	Thu Jun 06 2019 15:08:49 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: That was quick...

OMG!!!!!!!!!!!!!!!

FYI, I was just over at MGH and Xanterra is putting up a nice new version of the repeat photography exhibit as well as other disappearing glacier exhibits in the lower level of the lobby (I'm assuming you or Bill coordinated with them on these.). They look good.

On Thu, Jun 6, 2019 at 1:34 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> The new St. Mary exhibits were noticed:
>
> https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/
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> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
> 406-888-7933

--
Diane Sine
Many Glacier Lead Interpreter
Glacier National Park
Many Glacier Office: 406.732.7740 ext. 4 or 7741 ext. 4

Conversation Contents

St. Mary VC Exhibits

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon May 20 2019 16:54:10 GMT-0600 (MDT)
To:	Deborah Smith <debby_smith@nps.gov>, Lee Rademaker <lee_rademaker@nps.gov>
CC:	William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	St. Mary VC Exhibits

Hey Debby and Lee,

Nate should be in the visitor center tomorrow morning to help install the new relief map panels. He has a few things to do on the east side but is roughly aiming to be at the visitor center around 9AM.

-daniel

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Mon May 20 2019 20:09:52 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

Great! Thanks for the heads up. We'll have an eastside orientation/OSHA happening in the SMVC tomorrow starting at 9 am, so I may be pulled away briefly to help with that, but otherwise I'll be around the VC. Lee will also be around if there are questions.

Thanks again,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

I am a *proud* graduate of the GOAL Leadership Academy. Ask me about the program!

On Mon, May 20, 2019 at 4:54 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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>
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> -daniel
>
> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
> 406-888-7933

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed May 22 2019 10:21:10 GMT-0600 (MDT)
To:	"Smith, Deborah" <debby_smith@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

Hey all, how did the install go?

On Mon, May 20, 2019 at 8:10 PM Smith, Deborah <debby_smith@nps.gov> wrote:

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> Debby

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Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
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> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
> 406-888-7933

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Smith, Nathan" <nathan_smith@nps.gov>

From:	"Smith, Nathan" <nathan_smith@nps.gov>
Sent:	Wed May 22 2019 10:27:44 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: St. Mary VC Exhibits

It went well. They look great with the other panels, the wiring worked on the first try and Lee was a big help.

On Wed, May 22, 2019 at 10:21 AM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

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On Mon, May 20, 2019 at 4:54 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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-daniel

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed May 22 2019 10:31:12 GMT-0600 (MDT)
To:	"Smith, Nathan" <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

Awesome!

On Wed, May 22, 2019 at 10:27 AM Smith, Nathan <nathan_smith@nps.gov> wrote:

> It went well. They look great with the other panels, the wiring worked on the first try and Lee was a big help.
>
> On Wed, May 22, 2019 at 10:21 AM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:
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>>> Browning, MT 59417
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>>>> Visual Information Specialist
>>>> Glacier National Park
>>>> 406-888-7933
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>>
>> --
>> Daniel Lombardi
>> Visual Information Specialist
>> Glacier National Park
>> 406-888-7933

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Rademaker, Lee" <lee_rademaker@nps.gov>

From:	"Rademaker, Lee" <lee_rademaker@nps.gov>
Sent:	Thu May 23 2019 11:26:48 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: St. Mary VC Exhibits

It went well. All the lights work! One of the screws (that we re-used) slightly deformed the surface of the map panel. But, I think I can just push it back into shape on the warm day. Also, it isn't all that noticeable since it didn't poke through and is in a part of the image that hides it.

Lee Rademaker
Astronomy Coordinator / Lead Interpreter
Hudson Bay District
Glacier National Park
406-732-7791
Days off: Saturday / Sunday

On Wed, May 22, 2019 at 10:21 AM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> Hey all, how did the install go?
>
> On Mon, May 20, 2019 at 8:10 PM Smith, Deborah <debby_smith@nps.gov> wrote:
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> > Debby Smith
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> > Glacier National Park
> > 73 Hudson Bay Road Unit 1
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> > Daniel Lombardi
> > Visual Information Specialist
> > Glacier National Park
> > 406-888-7933

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

Conversation Contents

Re: St. Mary VC Exhibits

Deborah Smith <debby_smith@nps.gov>

From:	Deborah Smith <debby_smith@nps.gov>
Sent:	Wed May 22 2019 10:24:12 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject:	Re: St. Mary VC Exhibits

Looks good :-)

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

-------- Original Message --------
From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Date: Wed, May 22, 2019 10:21 AM -0600
To: "Smith, Deborah" <debby_smith@nps.gov>
CC: Lee Rademaker <lee_rademaker@nps.gov>, William Hayden <bill_hayden@nps.gov>, Nathan Smith <nathan_smith@nps.gov>
Subject: Re: St. Mary VC Exhibits

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> Debby Smith
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> Visual Information Specialist
> Glacier National Park
> 406-888-7933

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
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Conversation Contents

St Mary

"Smith, Nathan" <nathan_smith@nps.gov>

From:	"Smith, Nathan" <nathan_smith@nps.gov>
Sent:	Thu May 16 2019 09:41:25 GMT-0600 (MDT)
To:	William Hayden <bill_hayden@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	St Mary

I wanted to let you know samples of the St Mary exhibits are ready for viewing.

Thank You
Nate

Conversation Contents

paper

Attachments:

/10. paper/1.1 Bosson_et_al-2019-Earth's_Future.pdf

"Florentine, Caitlyn" <cflorentine@usgs.gov>

From:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Sent:	Mon May 13 2019 07:47:18 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	paper
Attachments:	Bosson_et_al-2019-Earth's_Future.pdf

--
Caitlyn Florentine, PhD
USGS Northern Rocky Mountain Science Center
215 Mather Drive
West Glacier, MT 59936
cflorentine@usgs.gov
303-548-7693

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon May 13 2019 09:41:22 GMT-0600 (MDT)
To:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Subject:	Re: paper

Thank you!

On Mon, May 13, 2019 at 7:47 AM Florentine, Caitlyn <cflorentine@usgs.gov> wrote:

> --
> Caitlyn Florentine, PhD
> USGS Northern Rocky Mountain Science Center
> 215 Mather Drive
> West Glacier, MT 59936
> cflorentine@usgs.gov
> 303-548-7693

--
Daniel Lombardi
Visual Information Specialist
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Earth's Future

RESEARCH ARTICLE
10.1029/2018EF001139

Key Points:
- First inventory and study of the 19,000 glaciers located in natural World Heritage sites is presented
- In response to anthropogenic warming, these glaciers are expected to lose 33% to 60% of their volume by 2100
- The conservation of World Heritage glaciers is paramount in a changing climate because of their key role in planetary ecosystems

Supporting Information:
- Supporting Information S1
- Table S1

Correspondence to:
J.-B. Bosson,
jeanbaptiste.bosson@gmail.com

Citation:
Bosson, J.-B., Huss, M., & Osipova, E. (2019). Disappearing World Heritage glaciers as a keystone of nature conservation in a changing climate. *Earth's Future*, *7*, 469–479. https://doi.org/10.1029/2018EF001139

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Disappearing World Heritage Glaciers as a Keystone of Nature Conservation in a Changing Climate

J.-B. Bosson[1], M. Huss[2,3], and E. Osipova[1]

[1]World Heritage Programme, International Union for Conservation of Nature (IUCN), Gland, Switzerland, [2]Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland, [3]Department of Geosciences, University of Fribourg, Fribourg, Switzerland

Abstract Since 1972, the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Convention aims to identify and protect sites of Outstanding Universal Value for future generations. However, growing impacts of climate change are of the utmost concern for the integrity of many sites. Here, we inventory the glaciers present in natural World Heritage sites for the first time. We found 19,000 glaciers in 46 sites located all over the world. We analyze their recent evolution, current state, and project their mass change over the 21st century. Our results are based on a comprehensive review of the literature as well as a state-of-the-art glaciological model for computing glacier responses up to 2100. Illustrating the strong influence of CO_2 emission scenarios and human actions on future ice loss magnitude, we project the wastage of 33% to 60% of the 2017 cumulative ice volume of 12,000 km^3 of World Heritage glaciers by 2100. Furthermore, we expect complete glacier extinction in 8 to 21 of the investigated World Heritage sites until the end of the century, depending on the climate scenario. We suggest that World Heritage glaciers should be considered as analogs to endangered *umbrella*, *keystone*, and *flagship species*, whose conservation would secure wider environmental and social benefits at global scale.

Plain Language Summary The World Heritage convention aims at protecting the Earth's outmost assets and commits humanity to transmit them to future generations. However, many World Heritage sites are affected by anthropogenic climate change. Here, we present the first study on the glaciers located within the natural World Heritage sites. We inventoried 19,000 World Heritage glaciers and projected their mass changes over the 21st century. The results emphasize that major glacier decline will occur in these iconic sites in future decades. Nevertheless, ice loss magnitude will vary by a factor of 2 according to CO_2 emission scenarios and thus human activities. This study points out how the conservation of World Heritage glaciers could serve as a leverage and a target to tackle the unprecedented issue of climate change. Glaciers are more than disappearing passive climatic indicators. They are key components of planetary ecosystems that influence global climate and sea level, as well as water fluxes, human activities, or biodiversity at the regional scale. The conservation of these iconic endangered features could thus mobilize global-scale conservation and climate mitigation benefits. In this context, we show how drastic reduction of emissions will rapidly curb melt rates and safeguard a large glacier volume on the long term.

1. Introduction

The Convention Concerning the Protection of the World Cultural and Natural Heritage was conceived to protect the planet's most significant and irreplaceable places from loss or damage (United Nations Educational, Scientific and Cultural Organization, 1972). It constituted a major advance in conservation strategies by linking together, above any spatial and temporal boundaries, the preservation of natural and cultural heritage. Today, 247 natural World Heritage sites are listed for their Outstanding Universal Value (OUV)—in terms of natural beauty or importance for geological and biological diversity and processes—committing states and the international community to make the utmost effort to conserve and transmit them to future generations. Although the 1972 World Heritage Convention did not identify anthropogenic climate change (Intergovernmental Panel on Climate Change, 2013, 2018) among the major issues, it now represents one of the most serious threats to natural sites and is the main source of future threat (Osipova et al., 2017). Recent studies have shown how direct or cascading effects of climate change lead to negative impacts on inscribed sites in various regions (Allan et al., 2017; Hughes et al., 2017; Reimann et al., 2018; Scheffer et al., 2015). Major changes are also documented in polar and mountainous environments, where

ongoing warming is amplified (MRI Working Group, 2015). The fate of glaciers appears especially troubling as their global decline is both observed and predicted (Intergovernmental Panel on Climate Change, 2013; Marzeion et al., 2018; Zemp et al., 2015). Although studies exist on some glaciers located in World Heritage sites, their particular conservation status—that is, their recognition as outstanding natural assets or components of ecosystems that have to be protected for future generations—is almost never considered, and no comprehensive assessment of their state has been carried out. This paper addresses this gap by comparing natural World Heritage sites and the globally complete Randolph Glacier Inventory (RGI; Pfeffer et al., 2014). This first identification of World Heritage glaciers allowed us to review the literature on their recent evolution and to explore the potential mass change during 21st century by using an updated version of the Global Glacier Evolution Model (Huss & Hock, 2015), a sophisticated approach to compute the individual response of glaciers.

2. Data and Methods

2.1. Data

The boundaries of the 247 natural World Heritage sites originate from the World Database on Protected Areas. Following the adoption of the World Heritage Convention in 1972, cultural and natural sites of OUV have been inscribed on the World Heritage list since 1978 and, with the exception of Antarctica, are currently present across the world.

Glaciers are dynamical ice masses formed by snow compaction. Outlines of all glaciers worldwide are provided by the globally complete RGI version 6.0 (RGI Consortium, 2017). The acquisition dates of the glacier outlines range from 1943 to 2013 but are typically from the first decade of the 21st century (Table S1 in the supporting information). We used global digital elevation models from various sources (Howat et al., 2014; Jarvis et al., 2008; Morin et al., 2016; Tachikawa et al., 2011) to extract and aggregate into 10-m elevation bands the topography of each glacier. Ice thickness distribution at the inventory date was calculated for each glacier by a numerical method for inverting bedrock elevation from surface topography relying on the principles of ice flow dynamics (Huss & Farinotti, 2012). In order to run the glacier evolution model at the global scale, we used monthly near-surface air temperature and precipitation data from the ERA-Interim Reanalysis (Dee et al., 2011) for the period 1980–2016. Results of monthly 2-m air temperature and total precipitation of the Fifth Phase of the Coupled Model Intercomparison Project (Taylor et al., 2012) for 2017–2100 were used for the future and were downscaled to all glaciers individually (Huss & Hock, 2015). We use projections from 14 global circulation models forced by three emission scenarios (Representative Concentration Pathways, RCP: Meinshausen et al., 2011; RCP 2.6, drastic reduction of greenhouse gas emissions; RCP4.5, intermediate scenario; and RCP8.5, high emissions).

2.2. Glacier Inventory in Natural World Heritage Sites

A World Heritage glacier inventory was established by intersecting the outlines of all natural World Heritage sites with those of the >200,000 glaciers of the RGIv6.0 (e.g., Figure S1). Most of the inventoried glaciers (94%) have their whole area encompassed within the World Heritage sites, whereas other glaciers have only a part of their area within the latter. As the Greenland ice sheet outlines are not included in the RGI, we used satellite-derived data (09.2016 MeASUREs Greenland Mosaics from Haran et al., 2017, and winter 2016–2017 glacier terminus position from reference; Joughin et al., 2017) to delineate the frontal zone of the Jakobshavn Isbræ in Ilulissat Icefjord, the glacier located in the only natural World Heritage site encompassing part of Greenland.

In order to investigate how future glacier evolution and possible disappearance will modify or jeopardize the OUV of the World Heritage sites that contain them, we analyzed the consideration of glaciers in official documents of inscription and in the statements of OUV. We found four different types of consideration for glaciers: (1) Glaciers were (among) the primary reasons for OUV, (2) they influence the wider OUV of the site, (3) they are recognized, but the site was inscribed only under biodiversity criteria, and (4) they are present but not recognized within OUV. A potential glacier decline will thus have no to crucial influence on the site's OUV and, hence, on the justification of the World Heritage status of a site.

2.3. Glacier Modeling

As illustrated for Southern Patagonia (Figure S1), some World Heritage glaciers only have small portion of their surface within the inscribed area. We thus removed the glaciers having less than 50% of their surface within the World Heritage sites to obtain a representative picture of the processes that will occur within the World Heritage sites. Hence, 18,452 World Heritage glaciers of the 19,039 inventoried (i.e., 97%) were considered during the glacier evolution modeling.

In order to assess the future evolution of all individual glaciers of the World Heritage, we rely on the established glacier model GloGEM (Huss & Hock, 2015). GloGEM computes glacier mass balance and associated changes in glacier geometry (thickness, length, and width) at the glacier-specific scale. The model operates in elevation bands of 10 m for each individual glacier. The surface mass balance is computed at monthly resolution as the sum of snow accumulation, snow, and ice melt and refreezing based on near-surface air temperature and precipitation time series. GloGEM also accounts for mass losses at marine- or lake-terminating glacier fronts due to iceberg calving and subaerial ablation approximated by a simple scheme (Oerlemans & Nick, 2005) that has been compared to direct observations in different regions of the Earth (Huss & Hock, 2015). At the end of each year, computed glacier mass changes are used to adjust each glacier's thickness distribution and spatial extent using an empirical parameterization relating total mass change to distributed ice surface elevation changes (Huss et al., 2010). The model thus does not explicitly include ice dynamics but parametrizes the corresponding effects on glacier geometry relying on a simple but widely used scheme (e.g., Li et al., 2015; Seibert et al., 2018). GloGEM was calibrated at the scale of individual regions of the RGI based on glacier mass change estimates derived from a multimethod consensus study (Gardner et al., 2013). Model results were compared to observations of glacier mass balance (in situ and geodetic measurements) available for all regions around the globe (Zemp et al., 2012) and glacier area changes indicating a generally good skill in reproducing past variation in glacier mass and area. For further details on the model, its calibration and downscaling procedures we refer to Huss and Hock (2015).

For the present study, the setup of GloGEM is widely consistent with the model version presented in Huss and Hock (2015). However, all model runs where updated using (i) the newest version of the RGI, that is, RGIv6.0, instead of RGIv4.0 as in Huss and Hock (2015), and (ii) time series of observed meteorological conditions were extended up to 2016. For some regions, this update has resulted in more accurate results for regions with an enhanced quality of glacier inventory data (e.g., central Asia), and for small glaciers experiencing large changes in the first decade of the 21st century.

2.4. Uncertainties

The results presented here are subject to uncertainties. First, except for Jakobshaven Isbrae (Ilulissat Icefjord, Greenland), the present World Heritage glacier inventory fully relies on the glacier outlines contained in the RGI. In some regions, glacier outlines are outdated. For instance, the nine glaciers of Yellowstone National Park listed in the RGIv6.0 seem to have disappeared already and/or are stagnant snow patches according to recent aerial photographs (imagery from *Google Earth* and *Plans* software). Our model also provides evidence for the likely disappearance of these glaciers by simulating complete glacier disintegration before 2005 (Figure S2). Nevertheless, the RGI remains the most complete source of glacier outlines at the global scale. In addition, we also analyzed aerial photographs in other natural World Heritage sites located in cold and mountainous environments to investigate if all World Heritage glaciers were included in the RGI. No large glaciers were found. However, existing remnant ice patches (e.g., in Pirin National Park, Gachev et al., 2016) or active rock glaciers (e.g., in Jiuzhaigou Valley Scenic and Historic Interest Area; 32°55′50″N, 103°53′E) having a potentially glacial origin (Berthling, 2011; Bosson & Lambiel, 2016) could indicate *recent* disappearance of active glaciers in a few World Heritage sites other than the 46 inventoried ones with glaciers.

Uncertainties also arise in projections of future glacier change using GloGEM from uncertainties in (1) the climate projections, (2) the data on initial glacier area and ice thickness, and (3) the simplifications and approximations in the model and the calibration procedure. Various sensitivity experiments performed by Huss and Hock (2015) have shown that factors (2) and (3) can importantly influence projected future glacier change of individual glaciers as no measurements of glacier-specific ice thickness are available at the global scale, many physical processes have to be strongly simplified in a global glacier model, and the downscaling

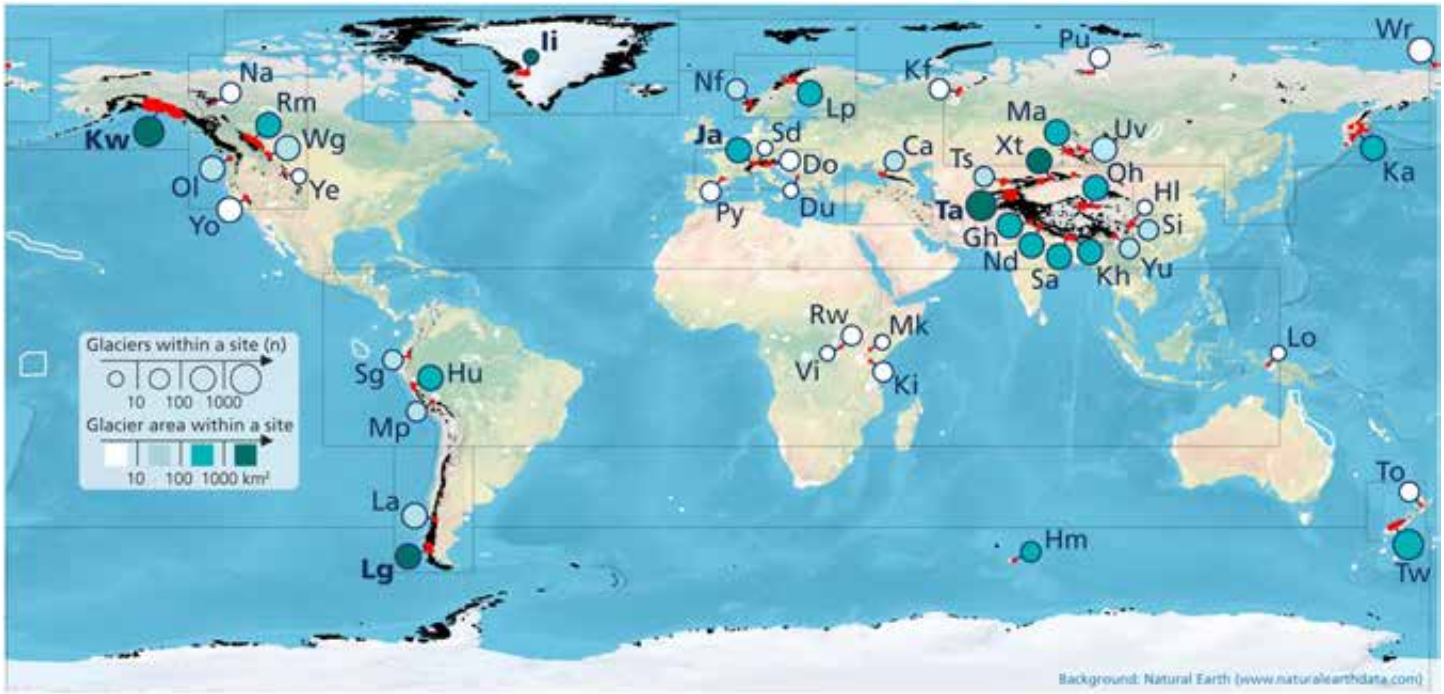

Figure 1. Glaciers (red dots) located in natural World Heritage sites (white polygons). Their number and area are scaled with circle size and color, respectively. Site names are abbreviated, and their full names are given in Table S2. Sites abbreviated in bold are those where glaciers were one of the primary reasons for inscription on the World Heritage List. Gray polygons are glacierized regions, and black dots correspond to all other inventoried glaciers (RGI Consortium, 2017, in addition to the two continental ice sheets in Greenland and Antarctica).

of meteorological variables to thousands of glaciers remains challenging. Nevertheless, validation of computed initial ice thicknesses and past mass balances against globally almost complete data bases of these variables has indicated a satisfactory performance of the model with only small regional biases (Huss & Farinotti, 2012; Huss & Hock, 2015). However, uncertainties in future climate forcing as evidenced by the partly large differences in projected temperature and precipitation changes of the individual global circulation models forced by the same CO_2 emission pathways are considerable and clearly dominate the overall uncertainties of the modeled glacier volume evolution of the 21st century (Marzeion et al., 2018). Here, we therefore consider uncertain climate evolution as the main uncertainty source and have used this factor to visualize and estimate overall uncertainty of glacier evolution in response to each RCPs.

3. Results

3.1. World Heritage Glaciers Inventory

We find that 19,039 glaciers have their whole or partial area within natural World Heritage sites. This corresponds to 9% of all glaciers on Earth (Figure 1 and Tables S2 and S3). Between one and several thousand glaciers, whose sizes range from 0.01 to 10^6 km^2, have been inventoried in 46 sites. Glaciers cover 55,950 km^2 within these sites, corresponding to 0.4% of the global glacier area (7.5% if one excludes the ice sheets in Antarctica and Greenland). New Zealand (76%; Table S1), Alaska (44%), and North Asia (26%) are the regions with the largest proportion of ice within World Heritage sites while Arctic Canada, Iceland, Svalbard, the Russian Arctic, and Antarctica have no World Heritage glaciers. Among outstanding glaciers, one of the fastest glaciers and largest iceberg producer (Jakobshavn Isbrae in Ilulissat Icefjord), the longest glacier outside continental ice sheets (Bering Glacier in Kluane Wrangell St Elias Glacier Bay Tatshenshuni-Alsek), and the highest glacier (on Mount Everest in Sagarmatha National Park) are designated as World Heritage. The largest glacier of Alaska (Seward Glacier in Kluane), central Europe (Grosser Aletschgletscher in Swiss Alps Jungfrau-Aletsch, Figure 2), central Asia (Fedchenko Glacier in Tajik

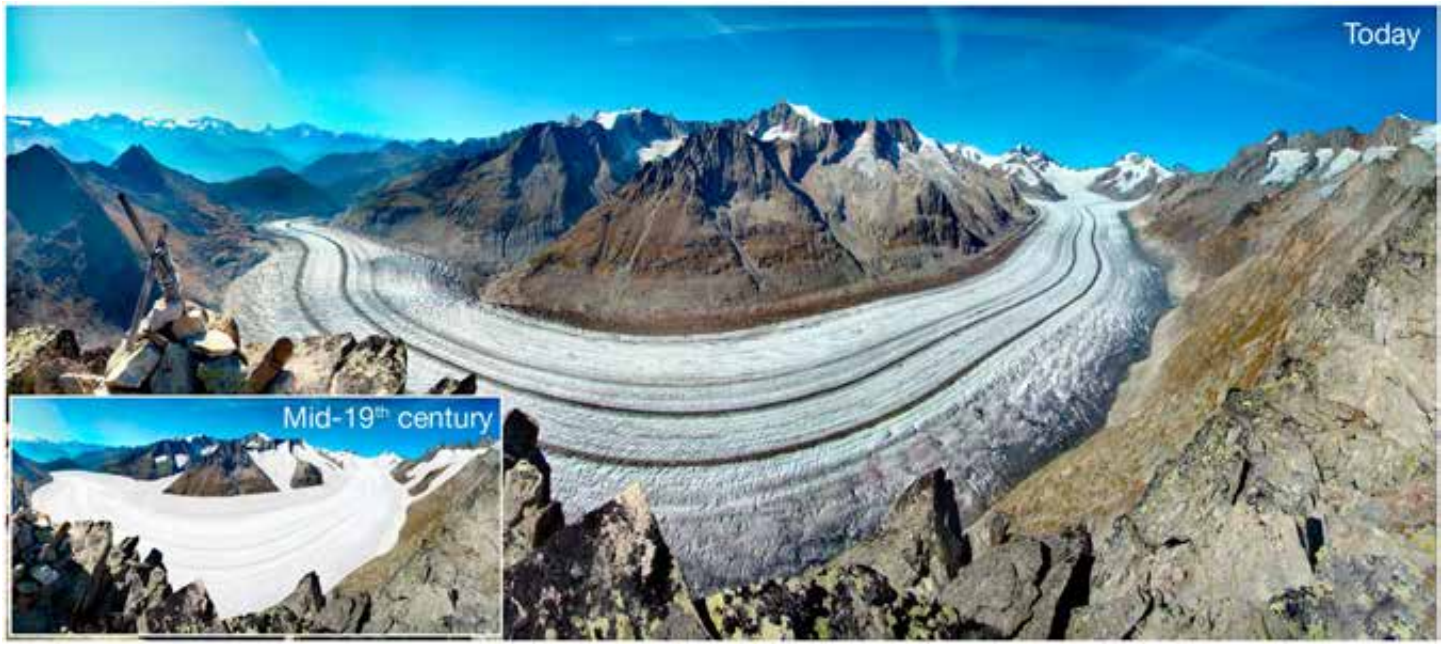

Figure 2. Current state and reconstitution of Grosser Aletschgletscher extent at the end of the Little Ice Age, in the midnineteenth century. This 23-km-long valley glacier is located in the World Heritage site Swiss Alps Jungfrau-Aletsch. It contributed significantly to the recognition of the World Heritage criteria vii (i.e., *aesthetic value*) and viii (i.e., *geological value*) that led to the inscription of this site in 2001. Grosser Aletschgletscher is by far the largest and longest glacier in the European Alps. It has lost more than 25% of its volume and has been partly dislocated since the midnineteenth century (Bauder et al., 2007). Illustrating the *long* response time of large glaciers to the post–Little Ice Age anthropogenic warming, Jouvet et al. (2011) showed that ~40% of its current volume would melt in future decades even if the climate would stabilize at the level of the year 2000. We project the melt of 66 ± 32% (RCP2.6) to 96 ± 7% (RCP8.5) of the current ice volume for this site by 2,100 (Table S4 and Figure S2), which will severely jeopardize its Outstanding Universal Value. Photograph: ©aletscharena.ch—Christian Rueegg, 2011. RCP = Representative Concentration Pathways.

National Park), Southern Andes (Pio XI in Los Glaciares National Park), and New Zealand (Tasman Glacier in Te Wahipounamu) are also listed.

The presence of glaciers is stated among the principal reasons for World Heritage inscription in five of the 46 sites (Table S2): Ilulissat Icefjord (Greenland), Kluane (Alaska), Los Glaciares National Park (Patagonia), Swiss Alps Jungfrau-Aletsch (Europe, Figure 2), and Tajik National Park (central Asia). In another 28 sites, glaciers contribute, together with other natural features, to their recognized OUV. In 13 sites, glaciers are not specifically mentioned as contributing to inscription.

3.2. Recent and Future Evolution of World Heritage Glaciers

Glaciers are among the best climate indicators in nature because their volume depends on air temperature, precipitation and energy exchange at the Earth's surface. Since the nineteenth century, by limiting snow precipitation and extending and intensifying melt periods, anthropogenic global warming has induced a worldwide glacier decline (Intergovernmental Panel on Climate Change, 2013; Marzeion et al., 2014; Zemp et al., 2015). Substantial ice loss with mostly increasing magnitudes since the 1990s affected World Heritage glaciers (e.g., Figure 2; Brun et al., 2017; Das et al., 2014; Kjeldsen et al., 2015; López-Moreno et al., 2016; Schaefer et al., 2015; Thompson et al., 2011). The largest one, Jakobshavn Isbrae, very likely experienced the most severe loss since the nineteenth century as surface and submarine ablation, ice flux and iceberg discharge noticeably increased. It accounted for ~6% of the Greenland ice loss between 1983 and 2003 (Kjeldsen et al., 2015) and for ~3% of global sea level rise between 2000 and 2011 (i.e., 1 mm, Howat et al., 2011). Retreat and thinning of other World Heritage glaciers locally led to their disintegration or even complete disappearance (e.g., López-Moreno et al., 2016; Thompson et al., 2011). Glaciers also likely disappeared recently in a few other World Heritage sites than those inventoried, as evidenced by remnant ice patches (e.g., Gachev et al., 2016). Within this period of overall decline, mass gain and glacier advances may have temporally and locally occurred at some of the sites (Mackintosh et al., 2017; Schaefer et al., 2015; Zemp et al., 2015),

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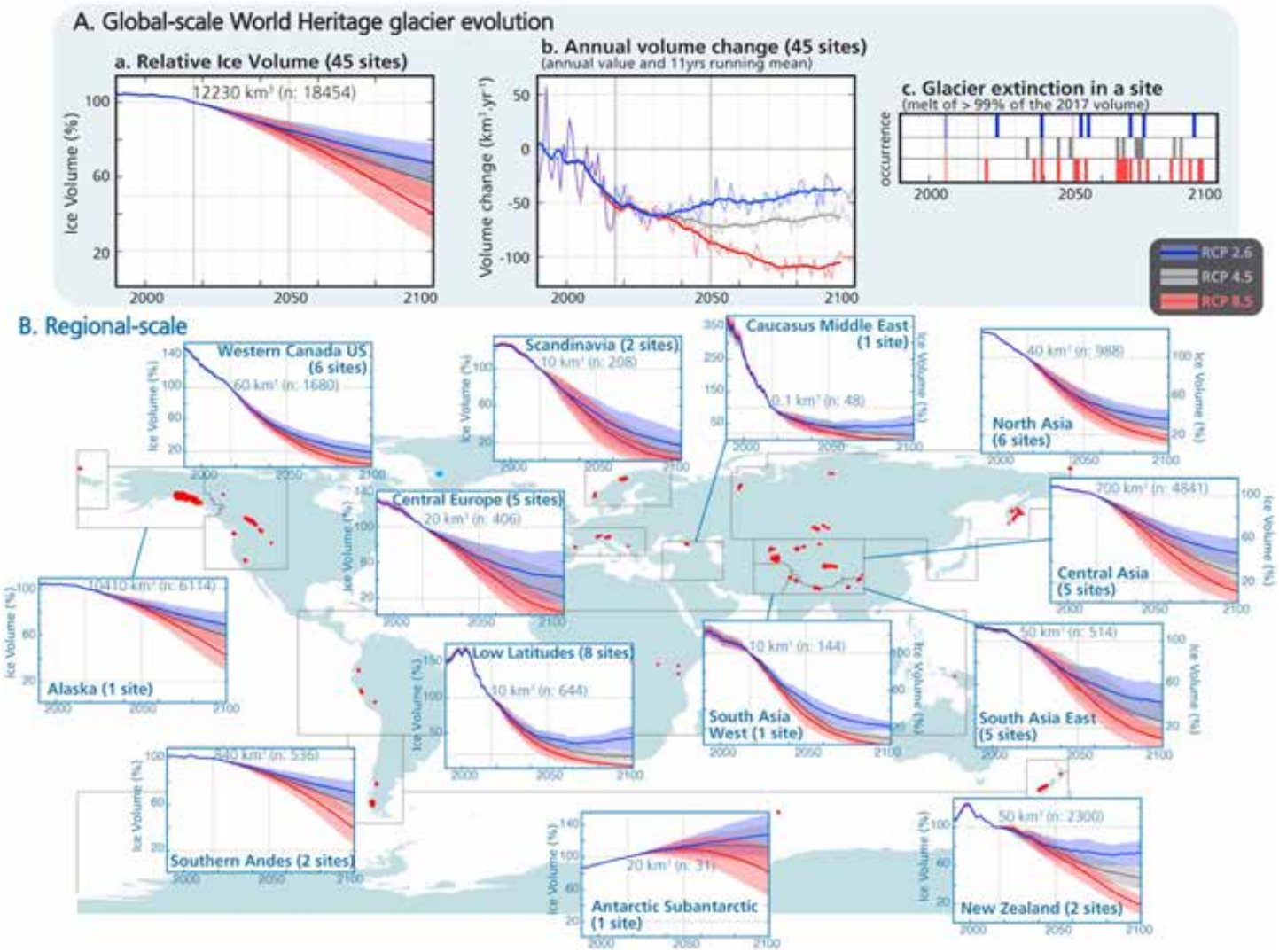

Figure 3. (a) Global and (b) regional 21st century evolution of glaciers located in natural World Heritage sites according to different CO_2 emission scenarios (RCP2.6, RCP4.5, and RCP8.5). Ice volume variations (multimodel mean of 14 general circulation models ±1 standard deviation) are relative to the 2017 ice volume (in cubic kilometer with the number of glaciers considered in each evolution diagram). On the map, the red dots correspond to the modelled World Heritage glaciers. RCP = Representative Concentration Pathways.

as a result of shorter-term decreases of atmospheric or oceanic temperatures, increases in precipitation, or variations of solar or volcanic activity.

We used a process-based model (Huss & Hock, 2015) to investigate the 21st century evolution of World Heritage glaciers. However, this model was not operable on Jakobshavn Isbrae due to the complexity of the involved glaciological and oceanographic processes for this site. According to existing modeling based on RCP4.5 (Church et al., 2013), this glacier will remain one of the largest contributors to sea level rise with 4–10 mm until 2100 (i.e., ~1% to 2.5% of the average global value). As the whole Greenland ice sheet, it responds with inertia to climatic variations and mass loss will very likely continue far beyond the end of the 21st century.

Overall, our model predicts a substantial ice loss for World Heritage glaciers throughout the 21st century (Figure 3a and Table 1). Mass loss by 2100 will account for 33 ± 11% (RCP2.6) to 60 ± 14% (RCP8.5) of the 2017 volume, corresponding to 3,600 ± 1,200 to 6,600 ± 1,600 km^3 of water, or 10 ± 3 to 18 ± 4 mm of sea level equivalent. All the annual (Figure 3a-b) and decadal means (Table 1) of glacier volume change are expected to be negative over the century, illustrating a continuous ice loss for all climatic scenarios.

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Table 1
Multimodel Means of the Computed Evolution of Glaciers Located in Natural World Heritage Sites Over the 21st Century

		RCP2.6	RCP4.5	RCP8.5
WH glaciers considered in the modelling (*n*)			18,452	
Ice volume (km^3)	2017	12,200	12,200	12,200
	2050	10,400 ± 600	10,200 ± 800	10,100 ± 800
	2100	8,200 ± 1,300	6,900 ± 1,500	4,900 ± 1,700
Relative volume change (%)	2017–2050	−15.1 ± 5	−16.2 ± 6.2	−17.6 ± 6.3
	2017–2100	−32.8 ± 10.7	−43.4 ± 11.9	−59.8 ± 14.1
Mass loss (Gt)	2017–2100	3,600 ± 1,200	4,800 ± 1,300	6,600 ± 1,600
Sea level equivalent (mm)	2017–2100	10.0 ± 3.3	13.2 ± 3.6	18.2 ± 4.3
Average annual volume change by decades (km^3/year)	2010–2020	−45	−48	−51
	2020–2030	−58	−57	−57
	2030–2040	−60	−61	−64
	2040–2050	−53	−67	−78
	2050–2060	−47	−72	−93
	2060–2070	−49	−71	−101
	2070–2080	−45	−65	−110
	2080–2090	−39	−63	−109
	2090–2100	−38	−63	−104
NWHS with ice melt >80% (*n*)	2017–2100	20	33	41
NWHS with ice melt >99% (*n*)	2017–2100	8	12	21
Glacier area (km^2)	2017	52,680	52,680	52,680
	2100	37,100 ± 5,200	31,600 ± 5,800	23,500 ± 6,900
Relative area change (%)	2017–2100	−29.6 ± 9.8	−40.0 ± 11.1	−55.4 ± 13.1

Note. Mass loss and sea level equivalent are computed assuming an ice density of 900 kg/m^3 and an ocean area of 3.625×10^8 km^2. WH = World Heritage. NWHS = Natural World Heritage sites.

However, the rate of mass loss will be reduced after the 2030s for RCP2.6 whereas it is expected to strongly increase for RCP8.5.

Due to heterogeneous climatic and topographic conditions, the evolution of World Heritage glaciers will differ at regional and site scales (Figures 3b and 4 and S2 and Tables 1, S4, and S5). However, except for the mostly balanced conditions modeled for Heard and McDonald Islands (Antarctic Islands), substantial ice loss will occur in all natural World Heritage sites. Over the 21st century, the magnitude of the relative ice melt will strongly depend on the size of glaciers in each site. Very small glaciers rapidly respond to climatic variations because it strongly modifies their mass balance and the accumulation area ratio (AAR, i.e., the ratio of the area of the accumulation zone compared to the entire glacier area, Figure 4). Hence, relative

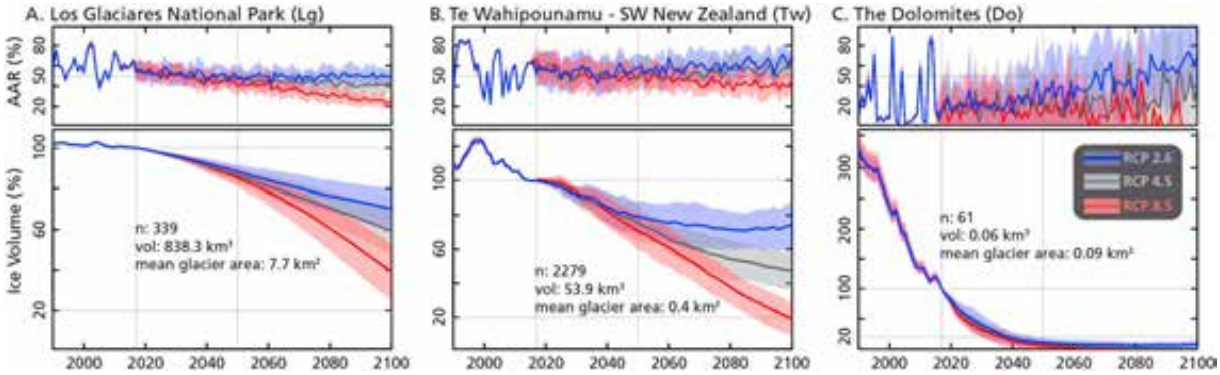

Figure 4. The 21st century evolution of glaciers located in three natural World Heritage sites according to different CO_2 emission scenarios (RCP2.6, RCP4.5, and RCP8.5). Ice volume variations (multimodel mean of 14 general circulation models ±1 standard deviation) are relative to the 2017 ice volume (in cubic kilometer with the number of glaciers and their mean area considered in each panel). Los Glaciares National Park (a; located in South America), Te Wahipounamu-SW New Zealand (b), and the Dolomites (c; central Europe) are displayed as examples of evolution in sites having mostly large ice cap glaciers, valley glaciers and very small glaciers, respectively. RCP = Representative Concentration Pathways; AAR = accumulation area ratio.

ice volume will rapidly decrease in sites with very small glaciers in a warming climate, while it will take longer in sites with large glaciers (Figure 4). If air temperature would stabilize in future decades as projected by RCP2.6, the smallest glaciers could rapidly find a new balance with climatic conditions and stop shrinking (AAR will be comprised between 50% and 70%) and even experience a mass gain if AAR values will exceed 70% as projected for the glaciers in Te Wahipounamu and the Dolomites (Figures 4b and 4c). Conversely, projections of glacier evolution in Los Glaciares National Park illustrate the slow response time of large glaciers (Figure 4a). The low AAR values (<50%) modeled for the glaciers in this site at the end of the 21st century indicate a strong imbalance between the remaining large ice volume and climatic conditions and thus the continuation of ice loss beyond 2100.

Overall, more than 80% of the 2017 ice volume is expected to have melted in 20 (RCP2.6) to 41 (RCP8.5) sites by 2100 and glacier extinction, defined here as the disappearance of more than 99% of the current ice volume, is forecasted in 8 (RCP2.6) to 21 (RCP8.5) sites (Figure 3a-c and S3 and Tables 1 and S4). Compared to ice volume in 2017, the difference between estimated volume losses by 2100 for RCP2.6 and RCP8.5 is smaller than 10% in 13 sites (e.g., Figures 4c and S3 and Table S4), reflecting the irremediable future vanishing of small glaciers in unfavorable environments. In other words, at such sites glaciers will disappear no matter which RCP scenario occurs. Conversely, this difference is above 25% in 20 sites (e.g., Figures 4a and 4b), emphasizing the strong influence of CO_2 emissions scenarios and, thus, human actions on the magnitude of ice loss. At the end of the century, the computed glacier geometry will be close to equilibrium with climate for RCP2.6 (mean AAR > 50% in 60% of the sites; e.g., Figures 4b and 4c and S4 and Table S4). However, a strong imbalance is modeled for RCP4.5 and RCP8.5 (mean AAR > 50% in only 31% and 3%, respectively, of the sites) and therefore suggests the continuation of ice loss far beyond 2100.

4. Discussion and Conclusion

Through the first complete inventory of glaciers located in natural World Heritage sites, the analysis of their recent evolution, and the modeling of their future mass change, this study shows that, beyond the presence of many outstanding glaciers and their particular internationally recognized World Heritage status, these glaciers are similar and representative of the other glaciers on Earth. From very small cirque glaciers to ice caps or part of the continental ice sheet, all types and sizes of glaciers can be found among the 19,039 World Heritage glaciers. Present in most of the glacierized regions on Earth (Pfeffer et al., 2014), they experienced the same widespread mass loss as other glaciers in response to recent anthropogenic warming (e.g., Zemp et al., 2015). Our projections on the intensification of their melt over the 21st century are in line with previous glacier modeling studies at the local, regional or global scale (e.g., Clarke et al., 2015; Kraaijenbrink et al., 2017; Marzeion et al., 2018; Radić et al., 2014; Zekollari et al., 2014). In comparison to a previous application of the global glacier model used in the present study (Huss & Hock, 2015), we find similar trends in glacier wastage, but results are based on the newest available input data and, hence, are assumed to be more accurate.

This ongoing major and unprecedented glacier decline highlights the threat posed to the World Heritage in a changing climate. The presence of glaciers has been recognized as a natural value and is often mentioned to justify the inscription of the 46 studied sites on the World Heritage list (Table S2). Hence, the strong ice loss, and moreover, the projected glacier extinction in 8 (RCP2.6) to 21 sites (RCP8.5) over the 21st century will strongly affect the integrity and value of many of these World Heritage sites. It could even directly question the recognized OUV in sites like Swiss Alps Jungfrau-Aletsch (Figure 2), Ilulissat Icefjord, or Kluane Wrangell St Elias Glacier Bay Tatshenshuni-Alsek, which have been inscribed at least partly for their exceptional glaciers.

These results complete the observations and projections made on the loss of other geological and biological assets in natural World Heritage sites in a warming climate (e.g., Allan et al., 2017; Hughes et al., 2017; Osipova et al., 2017; Scheffer et al., 2015). Despite their commitment to use utmost resources, states and international community fail to preserve and conserve some valued natural features for future generations, even in the most outstanding protected areas. The current situation of the Great Barrier Reef demonstrates the complexity of nature conservation in World Heritage sites in a changing climate. The World Heritage Committee considered inscribing this site as *in danger* as of 2015, due to the occurrence of climatically controlled coral bleaching events. To prevent this undesirable inscription, the Australian government adopted a

long-term sustainability plan (Normile & Dayton, 2014). However, the most serious bleaching event of at least 20 years occurred in 2016 (Hughes et al., 2017), illustrating that local and national efforts, as well as usual nature conservation tools, cannot address a global issue having the magnitude and the complexity of atmosphere and ocean warming. Loss and damage related to anthropogenic climate change could thereby lead to the designation of more and more World Heritage sites as *in danger* or with a *critical state of conservation* in the near future (Osipova et al., 2017). However, if the World Heritage status does not protect from climate change impacts, World Heritage sites currently serve to develop knowledge, mitigation, and adaptation policy and to raise public awareness of this issue. Increasing efforts are especially made since 2005 by the different involved stakeholders in terms of strategy and capacity building from the local to the global scale (e.g., United Nations Educational, Scientific and Cultural Organization, 2014).

In an increasing number of publications (e.g., Ceballos et al., 2017; Hughes et al., 2017; Intergovernmental Panel on Climate Change, 2018; Ripple et al., 2017; Steffen et al., 2018), the scientific community warns humanity against the critical state of climate, nature, and societies on Earth in the Anthropocene and shows that decisive actions have to be urgently taken to prevent unprecedented, damageable, and irreversible consequences. In this context and among other actions, World Heritage glaciers conservation could be both used as a leverage and a target for planetary-scale climate change mitigation. Indeed, the safeguarding of these iconic and important natural features could mobilize global-scale conservation and mitigation benefits. As for all glaciers and ice sheets on Earth, their preservation reinforces the compelling priority for strong and rapid reduction of greenhouse gas emissions and thereby a deep modification of human impacts on the climate. World Heritage glaciers are thus analogous to *umbrella species* (Simberloff, 1998), and their conservation will automatically allow and imply the conservation of other features threatened by global warming. As all glaciers and ice sheets, World Heritage glaciers have also the characteristics of *keystone species* (Simberloff, 1998) because of their disproportionately large impacts on nature and societies on Earth. Glaciers and ice sheets have an important influence on global climate and sea level (e.g., Intergovernmental Panel on Climate Change, 2013; Marzeion et al., 2018; Marzeion & Levermann, 2014; Steffen et al., 2018). In many regions, they strongly impact freshwater, sediment and biogeochemical fluxes, biodiversity, and geohazards and provide many *nature's contributions to people* (e.g., Díaz et al., 2018; Huss et al., 2017; Huss & Hock, 2018; Milner et al., 2017). Their vanishing will thus have significant natural, social, economical, and migratory cascading consequences and could contribute to push and lock our planet beyond a threshold where the Earth would become a dangerous and uncontrollable hothouse (Steffen et al., 2018). Endangered World Heritage glaciers are finally similar to *flagship species* (Simberloff, 1998) because these emblematic and sensitive features have a large potential to raise global awareness, especially in view of the clear international commitment to protect World Heritage sites from damage or loss.

All of this emphasizes the compelling need and opportunity to act against worldwide (World Heritage) glacier decline. Supporting recent findings (Marzeion et al., 2018), our results show how drastic reductions of emissions (notably the achievement of RCP2.6) will rapidly curb melt rates to safeguard a large glacier volume in the long-term, limiting sea level rise and other cascading consequences. Within this scope, individual and collective actions (e.g., Intergovernmental Panel on Climate Change, 2014, 2018; Ripple et al., 2017; Wynes & Nicholas, 2017) are proposed to achieve the rapid and far-reaching societal transition required to respect the commitments made during the first worldwide climate agreement in 2015 in Paris.

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Conversation Contents

St. Mary Exhibits

Attachments:

/11. St. Mary Exhibits/1.1 GL-06-300 updated MAY 2019.pdf
/11. St. Mary Exhibits/1.2 GL-07-400 May 2019 Revisions.pdf
/11. St. Mary Exhibits/5.1 GL-07-400 May 2019 Revisions.pdf
/11. St. Mary Exhibits/5.2 GL-06-300 updated MAY 2019.pdf
/11. St. Mary Exhibits/6.1 GL-07-400 May 2019 Revisions.pdf
/11. St. Mary Exhibits/6.2 GL-06-300 updated MAY 2019.pdf

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu May 09 2019 11:13:49 GMT-0600 (MDT)
To:	Lee Rademaker <lee_rademaker@nps.gov>, Deborah Smith <debby_smith@nps.gov>
Subject:	St. Mary Exhibits
Attachments:	GL-06-300 updated MAY 2019.pdf GL-07-400 May 2019 Revisions.pdf

One final review.

I changed the final sentence in GL-07-400

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu May 09 2019 11:44:30 GMT-0600 (MDT)
To:	Lee Rademaker <lee_rademaker@nps.gov>, Deborah Smith <debby_smith@nps.gov>
Subject:	Re: St. Mary Exhibits

Okay, Caitlyn approved these changes. Let me know what you think and I'll have Bill review one last time and then I'll send them to Nate to start fabrication.

On Thu, May 9, 2019 at 11:13 AM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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> 406-888-7933

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"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Thu May 09 2019 11:52:21 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>
Subject:	Re: St. Mary Exhibits

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Thanks again,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

I am a *proud* graduate of the GOAL Leadership Academy. Ask me about the program!

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu May 09 2019 12:01:27 GMT-0600 (MDT)
To:	"Smith, Deborah" <debby_smith@nps.gov>
Subject:	Re: St. Mary Exhibits

Awesome, thank you. I made those changes and will send to Bill now.

On Thu, May 9, 2019 at 11:52 AM Smith, Deborah <debby_smith@nps.gov> wrote:

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu May 09 2019 12:04:55 GMT-0600 (MDT)
To:	William Hayden <bill_hayden@nps.gov>
Subject:	Re: St. Mary Exhibits
Attachments:	GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf

Hey Bill,

I think these are ready to send to Nate Smith in the sign shop if you look them over one last time.

On Thu, May 9, 2019 at 12:01 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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"Hayden, William" <bill_hayden@nps.gov>

From: "Hayden, William" <bill_hayden@nps.gov>

Sent:	Thu May 09 2019 14:49:45 GMT-0600 (MDT)
To:	Nathan Smith <nathan_smith@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Fwd: St. Mary Exhibits
Attachments:	GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf

Hi Nate

These two files are for the St. Mary exhibits that we discussed yesterday. They are ready to be printed and laminated to the old exhibits.

Bill

---------- Forwarded message ---------
From: **Lombardi, Daniel** <daniel_lombardi@nps.gov>
Date: Thu, May 9, 2019 at 12:05 PM
Subject: Re: St. Mary Exhibits
To: William Hayden <bill_hayden@nps.gov>

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Daniel Lombardi
Visual Information Specialist
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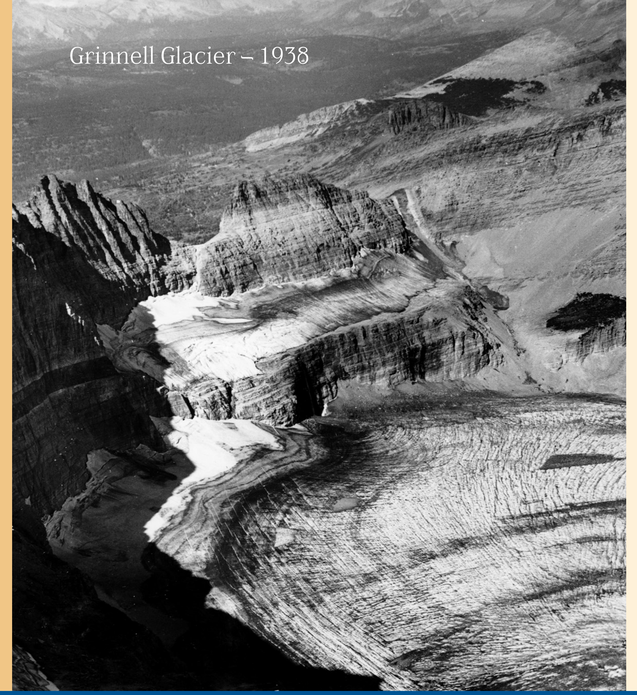
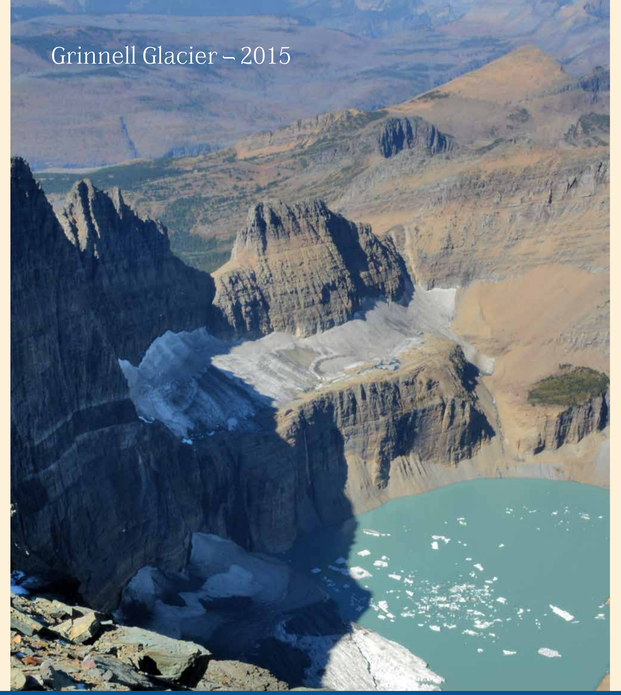
406-888-7933

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

Glaciers are moving masses of ice. During the Pleistocene—12,000–130,000 years ago—the massive glaciers shaping this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

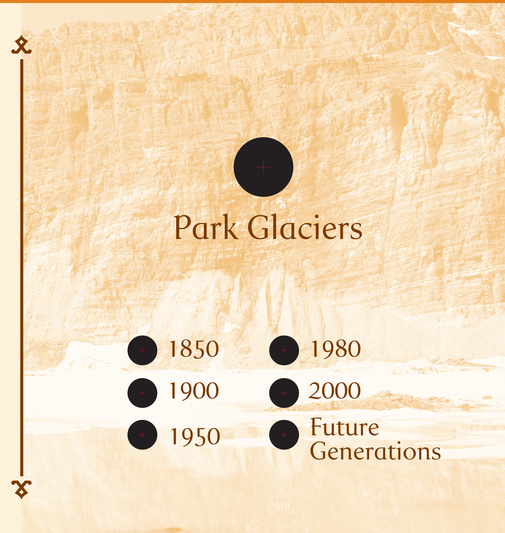
In 1850 there were about 150 glaciers in the park. In 2015, only 26 named glaciers remained in the park.

Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking. Grinnell Glacier, located high in the Many Glacier Valley, has lost 45% of its area in recent decades.

GLACIERS ON THE MOVE

GOODBYE TO THE GLACIERS

The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum size and number around 1850, at the end of the Little Ice Age. Today, they are all rapidly shrinking due to human-accelerated climate change. When they will completely disappear, however, depends on how and when we act.



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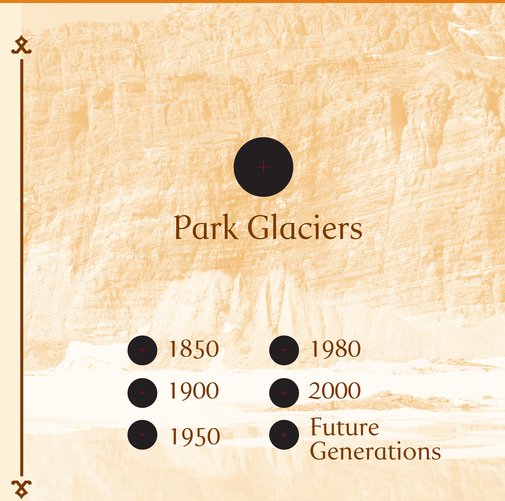

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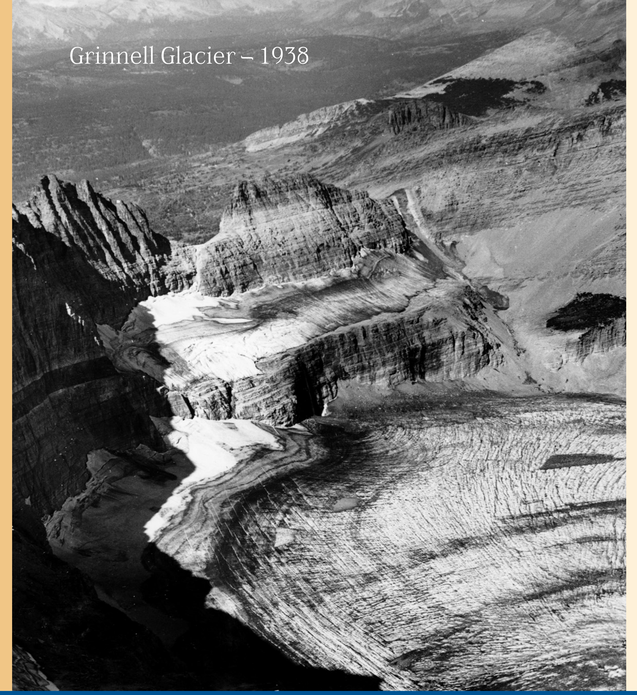

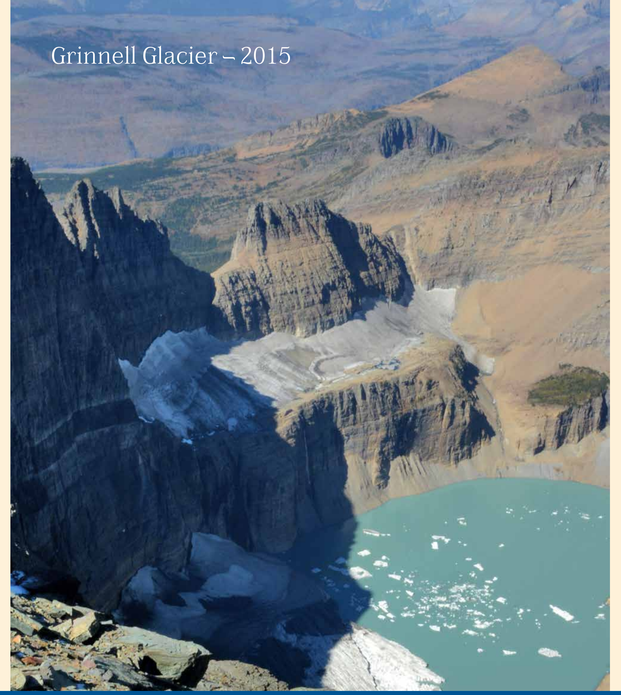

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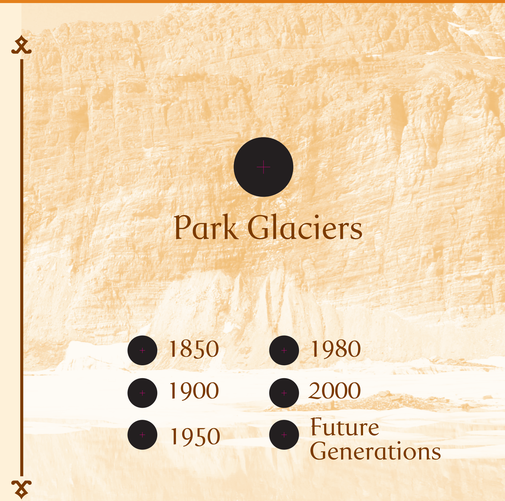
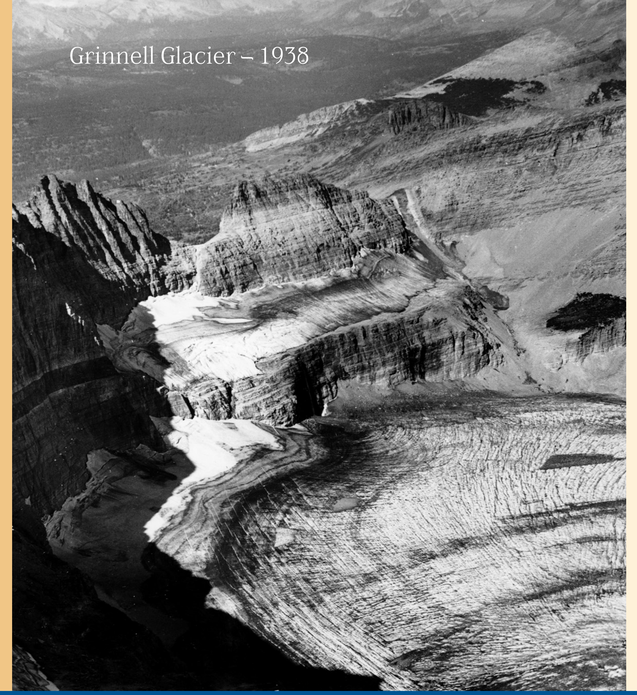
GOODBYE TO THE GLACIERS

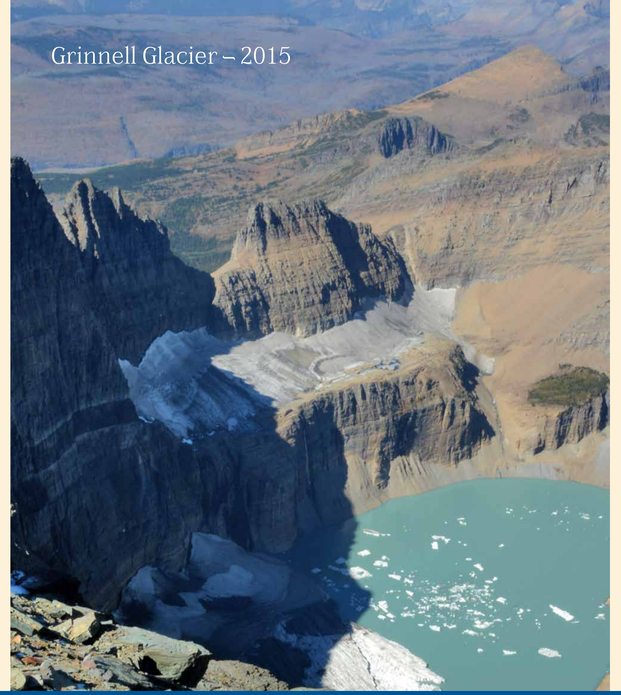
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum size and number around 1850, at the end of the Little Ice Age. Currently, they are rapidly shrinking due to human-accelerated climate change. When they will completely disappear, however, depends on how and when we act.



Glaciers are moving masses of ice. During the Pleistocene—12,000–130,000 years ago—the massive glaciers shaping this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

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GLACIERS ON THE MOVE

Conversation Contents

Chat with Caitlyn Florentine

Caitlyn Florentine <cflorentine@usgs.gov>

From:	Caitlyn Florentine <cflorentine@usgs.gov>
Sent:	Thu May 09 2019 11:10:41 GMT-0600 (MDT)
To:	daniel_lombardi@nps.gov
Subject:	Chat with Caitlyn Florentine

Caitlyn Florentine <cflorentine@usgs.gov>

From:	Caitlyn Florentine <cflorentine@usgs.gov>
Sent:	Thu May 09 2019 11:43:38 GMT-0600 (MDT)
To:	daniel_lombardi@nps.gov
Subject:	Chat with Caitlyn Florentine

Conversation Contents

ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

"Lisa Mckeon (Google Docs)" <d+MTAyMjI3MzM1MTgzNjYwODk4NTI5-MTE0NDMyNjM3NzQzMDk0NTM2Njc4@docs.google.com>

From:	"Lisa Mckeon (Google Docs)" <d+MTAyMjI3MzM1MTgzNjYwODk4NTI5-MTE0NDMyNjM3NzQzMDk0NTM2Njc4@docs.google.com>
Sent:	Fri Feb 08 2019 13:20:55 GMT-0700 (MST)
To:	<daniel_lombardi@nps.gov>
Subject:	ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

Lisa Mckeon added comments to ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

New

6 comments

New

Comments

Daniel Lombardi
Made a comment

Daniel Lombardi
Made a comment

Lisa Mckeon
Made a comment

Reply Open

Daniel Lombardi
Made a comment

Lisa Mckeon
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Lisa Mckeon
Made a comment

Reply Open

Daniel Lombardi
Made a comment

Lisa Mckeon
Made a comment

Reply Open

Google LLC, 1600 Amphitheatre Parkway, Mountain View, CA 94043, USA

You have received this email because you are a participant in the updated discussion threads. Change what Google Docs sends you. You can not reply to this email.

"William Hayden (Google Docs)" <comments-noreply@docs.google.com>

From:	"William Hayden (Google Docs)" <comments-noreply@docs.google.com>
Sent:	Fri Mar 15 2019 13:12:08 GMT-0600 (MDT)
To:	<daniel_lombardi@nps.gov>
Subject:	ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

William Hayden added comments to ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

New
2 comments

New

Comments

Daniel Lombardi
Made a comment

William Hayden
Made a comment

Reply Open

William Hayden
Made a comment

Reply Open

Google LLC, 1600 Amphitheatre Parkway, Mountain View, CA 94043, USA

You have received this email because you are a participant in the updated discussion threads. Change what Google Docs sends you. You can not reply to this email.

"Caitlyn Florentine (Google Docs)" <comments-noreply@docs.google.com>

From:	"Caitlyn Florentine (Google Docs)" <comments-noreply@docs.google.com>
Sent:	Thu May 09 2019 11:40:34 GMT-0600 (MDT)
To:	<daniel_lombardi@nps.gov>
Subject:	ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

Caitlyn Florentine added action items and comments to ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

New	Resolved
1 action item	1 action item, 1 comment

New

Action Items

Daniel Lombardi

Assigned to Caitlyn Florentine

Caitlyn Florentine
Made a comment

Reply Open

Resolved

Action Items

Daniel Lombardi

Assigned to Caitlyn Florentine

Caitlyn Florentine
Marked as done

Reply Open

Comments

Daniel Lombardi
Made a comment

Caitlyn Florentine
Marked as resolved

Reply Open

Google LLC, 1600 Amphitheatre Parkway, Mountain View, CA 94043, USA

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Conversation Contents

Re: Fwd: St. Mary VC Exhibits to Update

Deborah Smith <debby_smith@nps.gov>

From:	Deborah Smith <debby_smith@nps.gov>
Sent:	Thu May 09 2019 07:53:51 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: Fwd: St. Mary VC Exhibits to Update

Sure can. We have some stuff we need to move ASAP from the VC, but well proof this in about an hour.

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

-------- Original Message --------
From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Date: Wed, May 08, 2019 1:49 PM -0600
To: Deborah Smith <debby_smith@nps.gov>
Subject: Fwd: St. Mary VC Exhibits to Update

Can you review this? We are ready to have it fabricated.

Thanks!

-daniel

---------- Forwarded message ---------
From: **Lombardi, Daniel** <daniel_lombardi@nps.gov>
Date: Wed, May 8, 2019 at 12:11 PM
Subject: St. Mary VC Exhibits to Update
To: William Hayden <bill_hayden@nps.gov>

Final PDFs attached

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
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Conversation Contents

St. Mary VC Exhibits to Update

Attachments:

/15. St. Mary VC Exhibits to Update/1.1 GL-07-400 updated MAY 2019.pdf
/15. St. Mary VC Exhibits to Update/1.2 GL-06-300 updated MAY 2019.pdf
/15. St. Mary VC Exhibits to Update/2.1 GL-07-400 updated MAY 2019.pdf
/15. St. Mary VC Exhibits to Update/2.2 GL-06-300 updated MAY 2019.pdf

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed May 08 2019 12:11:35 GMT-0600 (MDT)
To:	William Hayden <bill_hayden@nps.gov>
Subject:	St. Mary VC Exhibits to Update
Attachments:	GL-07-400 updated MAY 2019.pdf GL-06-300 updated MAY 2019.pdf

Final PDFs attached

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Daniel Lombardi
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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed May 08 2019 13:49:47 GMT-0600 (MDT)
To:	Deborah Smith <debby_smith@nps.gov>
Subject:	Fwd: St. Mary VC Exhibits to Update
Attachments:	GL-07-400 updated MAY 2019.pdf GL-06-300 updated MAY 2019.pdf

Can you review this? We are ready to have it fabricated.

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From: **Lombardi, Daniel** <daniel_lombardi@nps.gov>
Date: Wed, May 8, 2019 at 12:11 PM

Subject: St. Mary VC Exhibits to Update
To: William Hayden <bill_hayden@nps.gov>

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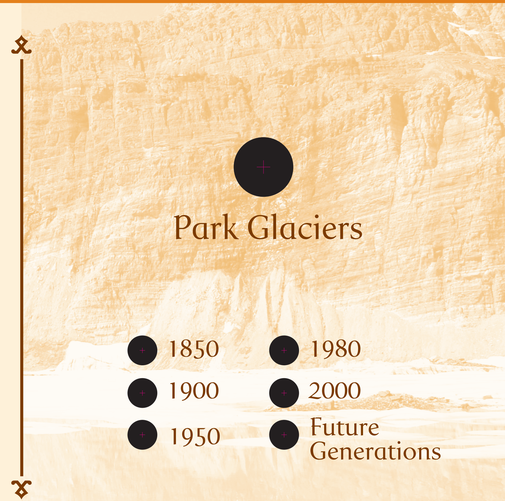
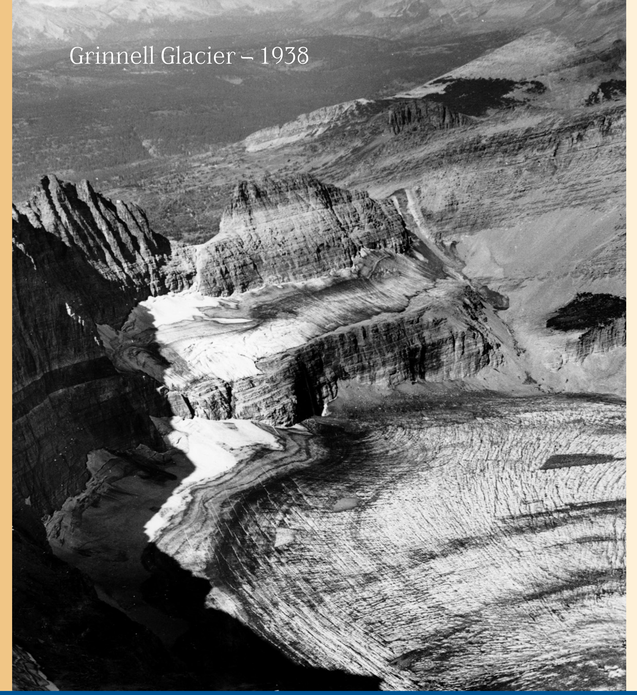
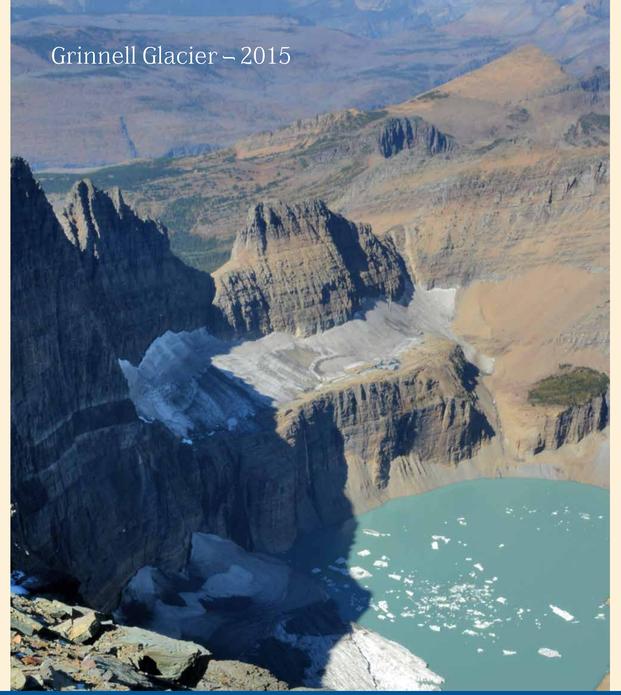


Glaciers are moving masses of ice. The glaciers that shaped the park were massive. During the Pleistocene—12,000–130,000 years ago—the glaciers covering this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





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In 1850 there were about 150 glaciers in the park. In 2015, only 26 named glaciers remained in the park.

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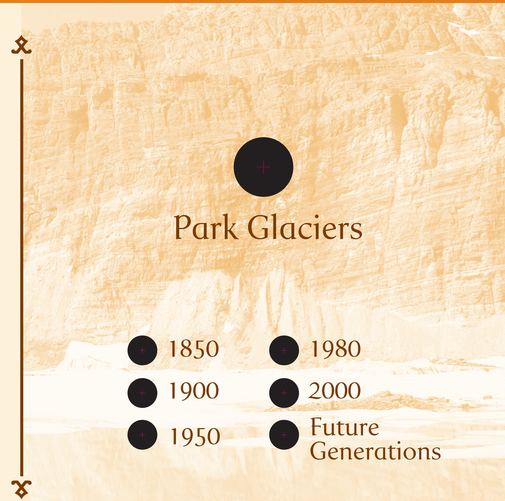

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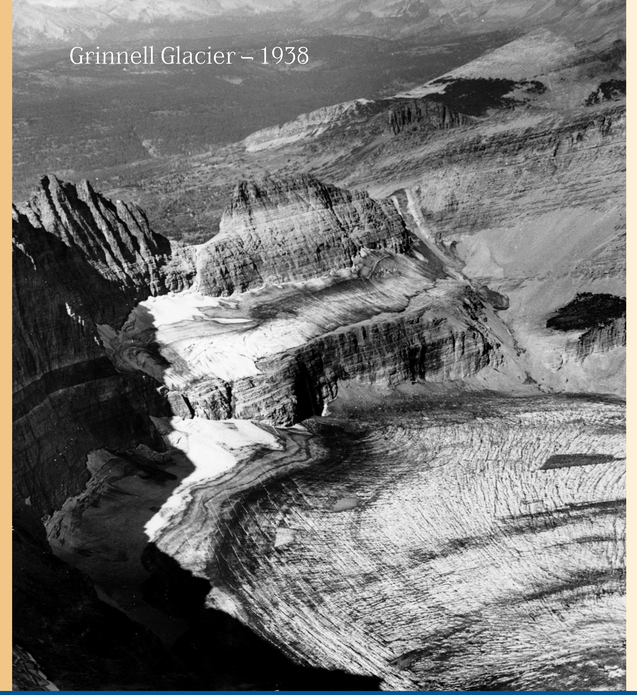

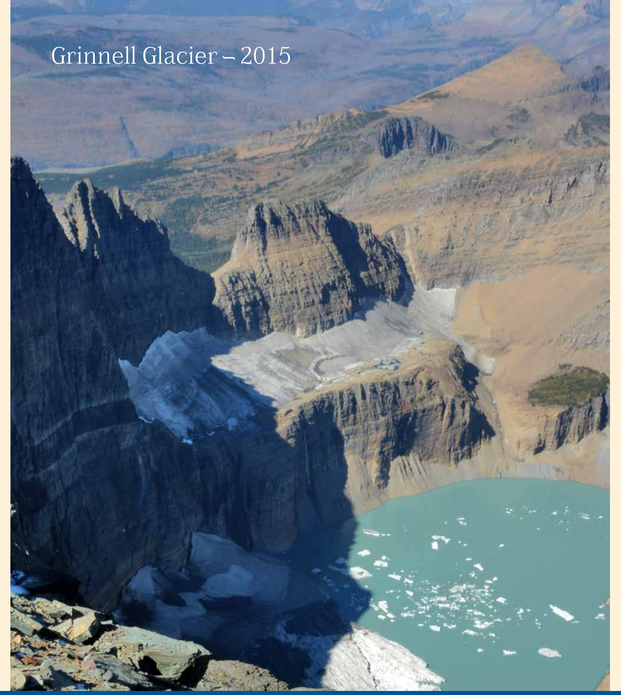

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GLACIERS ON THE MOVE

Conversation Contents

Glacier's hardest FAQ

Attachments:

/16. Glacier's hardest FAQ/2.1 Brown_2010_GPC.pdf
/16. Glacier's hardest FAQ/2.2 Clarke_2015_NatureGeoscience.pdf
/16. Glacier's hardest FAQ/2.3 Huss_2017_EarthsFuture.pdf
/16. Glacier's hardest FAQ/6.1 2019 Draft Climate Page Glacier Newspaper.pdf

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu Apr 18 2019 16:57:02 GMT-0600 (MDT)
To:	Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>
Subject:	Glacier's hardest FAQ

Can you help me answer these two questions? Linking me to more information would be fine/great. I'm hoping to start writing answers to these questions for the public.

And for the first question we might want to update the Jackson Glacier overlook exhibits because they say there are 26 active glaciers. We could at least add, "named glaciers."

How many glaciers are there in the park?

Is there time to save the park's glaciers?

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Florentine, Caitlyn" <cflorentine@usgs.gov>

From:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Sent:	Thu Apr 18 2019 18:29:21 GMT-0600 (MDT)

To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lisa Mckeon <lisa_mckeon@usgs.gov>, Chelsea Mikle <cmikle@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>
Subject:	Re: Glacier's hardest FAQ
Attachments:	Brown_2010_GPC.pdf Clarke_2015_NatureGeoscience.pdf Huss_2017_EarthsFuture.pdf

Hi Daniel,

Good call on updating the Jackson Glacier overlook to specify that "In 2015, only 26 *named glaciers* met the size criteria to be designated active glaciers."
Here is a first shot at answering these questions. Copying Chelsea and Dan here so that they can pipe in too.

Please do not go public with these answers yet. I am out in the field next week, but maybe we could get together to finalize the week after?
What time works for you on **Thursday, May 2**?

How many glaciers are there in the park?
public answer: There are a few dozen glaciers in the park. (encompasses all the techy details - timing, size criteria, etc. - outlined below)
or
technical answer: According to 2015 satellite imagery, there are 26 named glaciers in the park, but 32 glaciers overall. Glaciers are cohesive features >0.1 square km, identifiable as bare ice in late summer imagery when snow from the previous winter has melted.

Is there time to save the park's glaciers?
I need to think more about how to answer this one, but check out the attached papers for idea fodder. This sentence from the Huss abstract might inspire:
"With rising air temperatures and increased radiative forcing, glaciers will become smaller and, in some cases, disappear."

Thanks for being in touch and for leading the charge on this! I look forward to chatting more soon.

Cheers,
Caitlyn

On Thu, Apr 18, 2019 at 4:57 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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--
Caitlyn Florentine, PhD
USGS Northern Rocky Mountain Science Center
215 Mather Drive
West Glacier, MT 59936
cflorentine@usgs.gov
303-548-7693

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Fri Apr 19 2019 12:10:35 GMT-0600 (MDT)
To:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Subject:	Re: Glacier's hardest FAQ

Hi Caitlyn,

I'm available anytime on Thursday May 2nd. Maybe we should do lunch again.

I'm presenting the seasonal employee orientations every Monday for the next couple months, starting next week, and I've added a small glaciers/climate change section the orientation. That's why I was trying to get these answers - not necessarily to put on the website right away but to be able to chat with new seasonal employees about it.

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent: Fri Apr 19 2019 12:13:17 GMT-0600 (MDT)
To: "Florentine, Caitlyn" <cflorentine@usgs.gov>
Subject: Re: Glacier's hardest FAQ

Once, Lisa said something to me like, there may always be some kind of permanent snow and ice in glacier, if not active glaciers.

On Fri, Apr 19, 2019 at 12:10 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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"Florentine, Caitlyn" <cflorentine@usgs.gov>

From: "Florentine, Caitlyn" <cflorentine@usgs.gov>
Sent: Fri Apr 19 2019 12:24:25 GMT-0600 (MDT)
To: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject: Re: Glacier's hardest FAQ

Hi Daniel,

Gotchya - let's plan on lunchtime (noon) on Thursday May 2 then. Lisa is available that day too. We can meet here at our office, and then decide whether we want to relocate or stay near desks for accessing papers and figures and such.

"Always" is a strong word, but the general idea that perennial (lasting year-round) snow and ice will persist for many decades after active glaciers are gone is reasonable. Think about other mountain ranges where there are no longer proper glaciers, but snow fields and ground ice persist (e.g. Utah).

Could I check out your climate/glaciers slides for the orientation? Or will you be chatting only (i.e. no formal images or handouts)?

Thanks,
Caitlyn

On Fri, Apr 19, 2019 at 12:13 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed May 01 2019 18:27:59 GMT-0600 (MDT)
To:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Subject:	Re: Glacier's hardest FAQ
Attachments:	2019 Draft Climate Page Glacier Newspaper.pdf

Hey Caitlyn, are we still good to meet tomorrow?

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-daniel

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From:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Sent:	Thu May 02 2019 11:38:52 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: Glacier's hardest FAQ

Hey Daniel,

Yes, we are still on to meet today. See you in a bit. I will give your newsletter draft a read and think so we can mull it over together at lunch. Thanks.

Cheers,
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On Wed, May 1, 2019 at 6:28 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

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Article *in* Global and Planetary Change · November 2010

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Cirque glacier sensitivity to 21st century warming: Sperry Glacier, Rocky Mountains, USA

Joel Brown [a,b,*], Joel Harper [a], Neil Humphrey [c]

[a] Department of Geosciences, University of Montana, 32 Campus Dr., Missoula, MT 59812, USA
[b] Center for Geophysical Investigation of the Shallow Subsurface, Boise State University, 1910 University Dr., Boise, ID 83725, USA
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ABSTRACT

The interpretation of climate change based on the behavior of small cirque glaciers is not always straightforward or unique. In this study of Sperry Glacier, Glacier National Park, Montana, we model future change of the glacier under 11 different warming scenarios. The scenarios vary from no warming from present conditions to warming at a linear rate of 10 °C/century. We assume constant precipitation and only consider change invoked by warming. Our cellular automata model is based on simple rules that account for mass balance gradient, aspect, avalanching, and the flow of ice to redistribute mass. We constrain the model with glaciological data including georadar-measured ice depth, field-measured surface mass balance, and field-mapped ice surface topography. Under the most probable temperature increase based on downscaled OA-GCM output for the IPCC A1B scenario, we conservatively estimate the glacier persisting through at least 2080. By comparing glacier volume responses to different warming scenarios we elucidate a relationship between the magnitude of temperature change and the sensitivity of the glacier to small variations in the temperature increase. We find that the greater the magnitude of the temperature increase, the less sensitive the glacier area and volume become to slight differences in the warming rate. If we generalize this relationship to the region, we expect that a small change in climate will produce varying responses for glaciers throughout the region, whereas the glacier response to a large change in climate will likely be very similar over the entire region.

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1. Introduction

Area and volume adjustments of mountain glaciers have important impacts on society and natural systems. Most notable are the contributions of mountain glaciers to sea level rise (e.g., Meier and Dyurgerov, 2002; Bahr et al., 2009), and the influence of mountain glaciers on water resources and geomorphic hazards (e.g., Moore et al., 2009; Leiva et al., 2007). Since mountain glaciers are considered sensitive indicators of climate, they are used to detect and monitor local climate change in regions not typically monitored by instrumentation (e.g., Haeberli et al., 2007). Further, observations of glacier change are independent from potential issues related to the location, instrumentation, and processing of weather station data. Consequently, the general global retreat of mountain glaciers (Dyurgerov and Meier, 2000) is commonly cited as corroborating evidence for 20th century climate warming of the instrumental temperature record. For example, Oerlemans (2005) used the length records of 169 glaciers located around the world to construct a quantitative record of 20th century warming, and found that the glacier record agreed remarkably well with the instrumental record.

With projected increases to the rate of warming in the 21st century (IPCC, 2007), a general acceleration of rates of glacier retreat appears likely. For many small mountain glaciers, projecting their recent rate of retreat forward implies they will disappear within the 21st century (e.g., Nesje et al., 2008). However, the small glaciers within a region do not always advance or retreat at the same rate as large ones (Granshaw and Fountain, 2006; Fountain et al., 2009) and past advances or retreats of a glacier may not indicate how that glacier will change in the future. As mountain glaciers become small, many begin to occupy little more than the area below their cirque headwall. Near the cirque, winter snow accumulation is often enhanced from wind drifting and avalanching from the steep cliffs above, while radiation shading reduces summer ablation (Kuhn, 1995). Consequently, cirque glaciers are sometimes considered products of topography and therefore inappropriate indicators of climate variability and change (Kuhn, 1995). In addition, climate change within a region is not typically spatially uniform (e.g., Shindell and Faluvegi, 2009). Therefore, similar glaciers in different basins within the same region may not experience identical changes in climate and thus may have slightly different volume and area changes.

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doi:10.1016/j.gloplacha.2010.09.001

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Some small cirque glaciers may be more (or less) sensitive to climate change than other small cirque glaciers, making the interpretation of climate based on small glaciers difficult. In the Cascade Mountains of Washington State, U.S., larger glaciers lost less fractional area than smaller glaciers during last half of the 20th century (Granshaw and Fountain, 2006). Further north in a western Canadian mountain range, DeBeer and Sharp (2009) found that 75 of 86 small glaciers showed no observable size change during a similar time period. The lack of change implies that either this mountain region experienced no late 20th century warming, or that the small glaciers failed to respond to any warming. The authors suggest the lack of glacier change was due to the small size and sheltered locations of glaciers which allowed them to be roughly in balance with late 20th century climate conditions. In a study covering ~10^6 km^2 of western Canada between 1985 and 2005, Bolch et al. (2010) show highly variable reductions in area of glaciers less than 5 km^2, but many showing reductions of several tens of percent. Hence, projecting future change of small glaciers, or interpreting their ongoing changes, requires detailed understanding of the circumstances dictating their climate sensitivity.

Here we examine the climate sensitivity of a small cirque glacier (~0.8 km^2) in the northern Rocky Mountains, USA. Rather than analyze historical variations, we investigate the response of an existing glacier to a wide range of potential future warming scenarios. Our purpose is to use this glacier for which we have detailed field measurements to explore the processes dictating the climate sensitivity of small cirque glaciers. We find that under large-magnitude warming the glacier undergoes rapid area and volume reductions that are insensitive to minor variations to the warming rate. Under small-magnitude warming, however, slight differences in the warming rate yield large volume and area differences in the glacier.

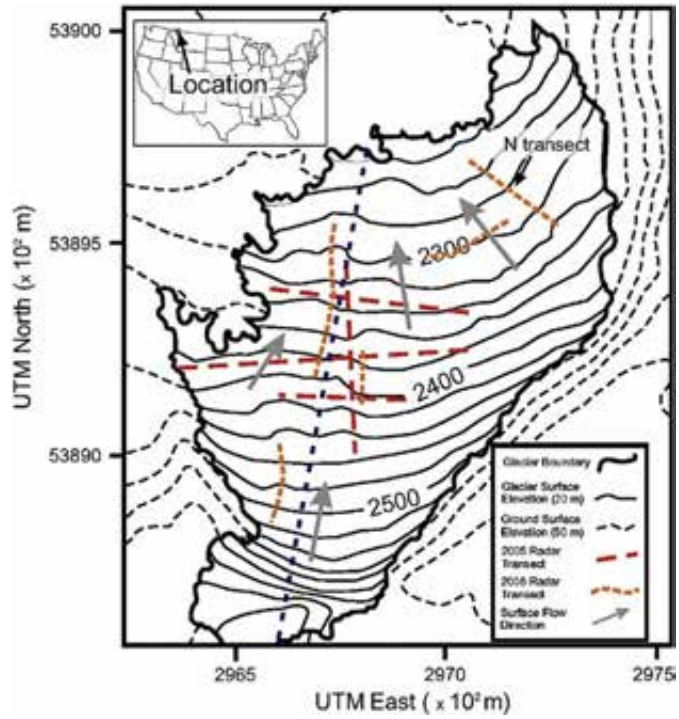

Fig. 1. Topographic map of Sperry Glacier surface derived from GPS measurements. Red dashed lines show location of 5 MHz radar transects collected in 2005, orange dashed curves show location of 5 MHz radar transects collected in 2008. Gray arrows indicate direction of ice flow. The blue dashed line trending roughly North-South is the location of the profiles in Fig. 6. The location of radar transect that is shown in Fig. 2 (N transect) is labeled.

2. Study glacier and glaciological setting

Sperry Glacier is a small cirque glacier located in Glacier National Park, Montana. The glacier is ~1 km wide, ~1 km long, has an average slope of ~10°, and sits beneath a cirque wall that extends upward 100–300 m (Fig. 1). Historic photographs reveal that since the start of the 20th century Sperry Glacier has lost approximately 78% of its area (Pederson et al., 2006) and has incurred a corresponding (but unquantified) reduction in volume. The climate conditions at Sperry Glacier during this period are undocumented, but during this time period global mean temperatures rose ~0.8 °C (Hansen et al., 2006) and some western Montana records experienced rises in extreme and seasonal average temperatures (Pederson et al., 2010). Historical trends of retreat of two other glaciers in Glacier National Park imply that projected 21st century warming could cause them to disappear in the next few decades if those trends were to continue (Hall and Fagre, 2003). However, we can make a zero-order estimate of Sperry Glacier's minimum longevity by applying the recent ablation rate at the terminus (−2 m/year) to the entire glacier, which we assume to average 35 m deep (this ablation rate and ice depth are justified below). This yields a time constant of ~18 years. Considering that this estimate assumes a very high ablation rate with no mass accumulation it is apparent that the glacier's lifetime will extend substantially beyond 18 years.

3. Methods

Future changes to mountain glaciers have been investigated with models of differing complexity and computational expense. For example, Paul et al. (2007) used a highly simplified approach that combines hypsographic analysis with an accumulation area ratio and neglects the redistribution of mass by ice flow. This approach requires minimal computational resources and therefore enables large regions (i.e., the Alps) and a wide variety of future scenarios to be explored (e.g., Paul et al., 2007). Schneeberger et al. (2003) used a much more complex approach by coupling an Atmosphere-Ocean General Circulation Model (OA-GCM), a glacier mass-balance model, and a glaciological flow model, which obviously required significant computational power as well as detailed input data for each modeled glacier.

Here we use an intermediate level of model complexity to investigate the response of Sperry Glacier to various warming scenarios. We model current and future glacier-climate conditions with a model constrained by field measurements of the glacier's surface mass balance and ice thickness. Our approach addresses 3-dimensional topography and incorporates vertically integrated ice flow dynamics, but our model is highly simplified and computationally inexpensive. The advantage of this approach is that it allows us to explore many different warming scenarios without neglecting mass transfer. A high degree of uncertainty surrounds future climate change and our aim is not to forecast the future of Sperry Glacier specifically. Rather, our goal is to investigate the range of responses of this small cirque glacier to different degrees of warming and to examine the glacier's sensitivity to different magnitude temperature variations.

3.1. Model construct and input

To simulate the mass balance and motion of Sperry Glacier we use a cellular automata (CA) model adapted from Harper and Humphrey (2003). The CA model uses a set of rules to accumulate, ablate, and move units of water equivalent over topographic cells of a landscape. The CA model requires as inputs Digital Elevation Models (DEMs) of the glacier surface and bed, and the annual net mass balance (B_n) defined according to elevation, slope, and aspect. The origin of the mass balance inputs are described in more detail in Section 3.1.2 (below). An annual time step in the modeling sequence consists of

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adding the water equivalent of the B_n (positive or negative) to each cell of the DEM. Mass is then transferred between cells via "avalanching" and "ice flow" (described below in Section 3.1.3). Iterations of mass transfer occur until no cells satisfy flow or avalanche criteria. In other words, the model converges each year when the glacier geometry fully adjusts by mass transfer to the mass gains and losses for that year. After the CA model converges, the surface DEM is updated to account for the small changes in glacier thickness and areal extent. This updated DEM is then used as the initial condition for the next annual time step and the process is repeated.

The model converts surface and bed DEMs from orthogonal to hexagonal cells. This allows for six degrees of freedom for particle motion between adjacent cells. Both avalanching and ice flow criteria are dependent on surface slope; thus, each cell has six slope values with associated directions. We compute the slope from the difference in elevation between cells divided by the distance between the centers of the cells. After the surface DEM is updated in surface slopes are recalculated for the subsequent time step.

3.1.1. Ice surface and bed topography

We used field measurements to determine the elevation of the current glacier surface, the current glacier volume, and the elevation of the bed surface. We measured the current elevation of the glacier surface in 2008 with GPS data collected with Trimble GeoXH and Trimble R7 receivers. The error of the GPS measurements is less than 1 m in the x and y directions and ~1 m in the vertical direction. We used a Kriging algorithm to generate a 10-m ice surface DEM and combined it with a 10-m terrain DEM (available from the U.S. Geological Survey) to include adjacent bedrock topography.

To measure the glacier thickness we used a 10-MHz Narod Geophysics type georadar transmitter and oscilloscope receiver. Our data were collected on 5-m spacing along transects and were georeferenced using a hand-held GPS receiver (accurate to 1–3 m). In total we collected nine transects, four in 2005 and five in 2008 (Fig. 1). We identified the two-way travel time (TWT) of the first reflection of the bed for each trace and converted the TWT to depth assuming a constant radar velocity of 0.168 m/ns (Fig. 2). Based on this propagation velocity, the ¼ wavelength resolution (Annan, 2005, p. 380) of the radar is ~4.2 m. We assume that all reflections come from directly below the acquisition point and we used a Kriging gridding algorithm to interpolate the ice depths over the area covered by Sperry Glacier using the edge of the ice surface as zero depth points. The final bed surface topography was generated by subtracting the interpolated ice thickness from the surface DEM. The surface and bed DEMs serve as initial condition inputs for our model runs.

3.1.2. Mass balance

Our model requires a prescribed function for mass balance versus elevation. Our function is based on 2 years of field measured surface mass balance and other meteorological and glaciological measurements in the basin (Reardon and Harper, unpublished USGS report). The function consists of two different linear gradients, one for above the ELA and one for below the ELA (Fig. 3). We generated the lower mass balance gradient by linearly fitting field observations of net annual mass balance vs. elevation. The data used to determine the lower elevation mass balance gradient were primarily acquired in the ablation area of the glacier and were spatially averaged across the width of the glacier. We found the mass balance gradient in the lower elevations to be $+7.5\times10^{-3}$ m of water equivalent per 1 m rise in elevation (0.0075 m m^{-1}). A net ice loss of ~2 m water equivalent occurred at the terminus (~2300 m elevation contour) all 4 years that we measured mass balance. Based on the mass balance gradient upward from the terminus, the ELA should be located at ~2570 m. However, field measurements and late summer photographs (Fig. 4) indicate that the ELA is actually lower, ranging between about ~2420–2550 m (depending on aspect). We attribute this lowered ELA and calculated climatic ELA to avalanching, wind drifting, and lower melt rates due to shading on the upper reaches of the glacier; which are represented by a higher mass balance gradient in the accumulation zone. After avalanching and flow are accounted for, the modeled ELA matches recent observations of the position of the observed ELA.

Sperry Glacier occupies a north-facing basin, but the surrounding topography with more southerly aspect and similar elevation range does not support perennial ice. To account for aspect-dependent mass balance we defined six aspect directions based on direction of the steepest slope for each cell and allowed positive mass balance only on the three north-most facing aspects. This matches present and historical observations, with ice existing at Sperry Glacier but not on adjacent southerly aspects.

3.1.3. Mass transfer

Ice movement is modeled by assuming that flow will occur when basal shear stress (τ_b) exceeds a critical value of 10^5 Pa (Nye, 1951). Hence, the model utilizes the common simplification that ice deforms as a pure plastic (Paterson, 1994; Hooke, 1998) and both ice deformation and basal sliding act to keep τ_b just below a yield stress. When τ_b exceeds 10^5 Pa in a cell, enough mass is transferred out of that cell to bring τ_b to just below the yield stress. Basal shear stress is calculated as:

$$\tau_b = \rho_i g h \sin(\theta), \tag{1}$$

where ρ_i is the density of ice (900 kg m^{-3}), g is the acceleration due to gravity (~9.8 m/s), h is depth of ice, and θ is defined as $\tan^{-1}(\Delta Z/\Delta d)$

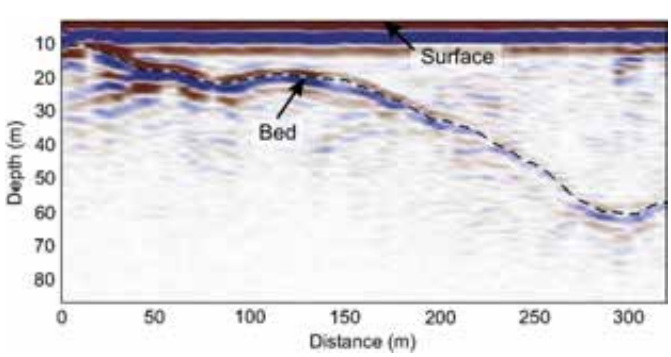

Fig. 2. Radar transect from Sperry Glacier. The bed reflection is clear across the profile. Depths are calculated with an assumed constant velocity of 1.68x10^8 m/s. The location of the transect (N transect) is shown on Fig. 1.

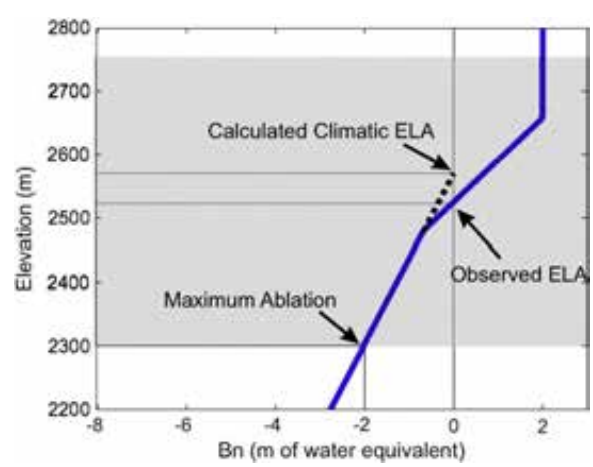

Fig. 3. Mass balance curve used as input for modeling. Elevation range spanned by Sperry Glacier is delineated by the gray shaded area. Locations of the calculated climatic ELA, observed ELA, and maximum ablation elevation are marked.

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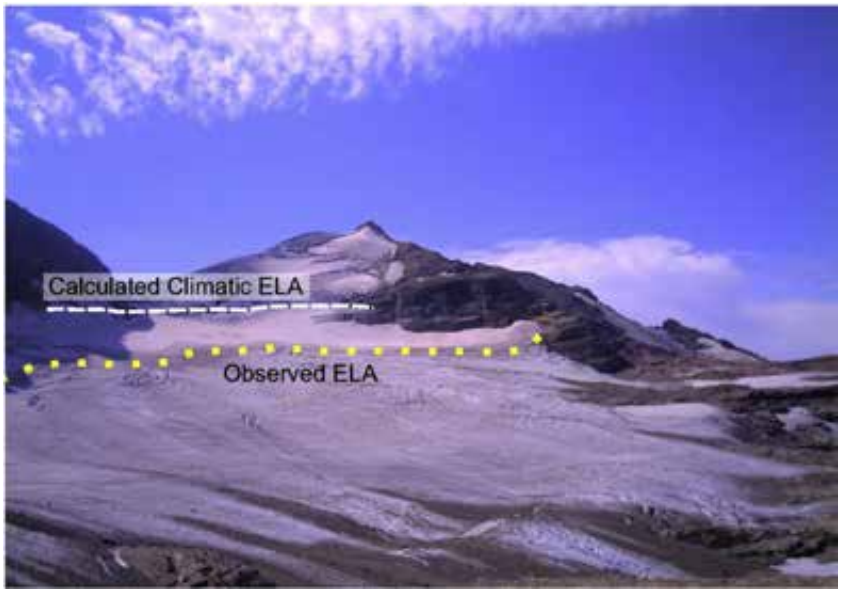

Fig. 4. Photograph of Sperry Glacier taken on 8-31-2007 as part of a time-lapse photo study. The approximate location of the calculated climatic ELA is marked with a white dashed curve; the observed ELA is marked with a yellow dotted curve. The location of the observed ELA in 2007 was higher than in all other observed years. The region of the glacier that is in view in this photograph is approximately 1 km.

where ΔZ is the difference between adjacent cell surface elevations and Δd is the distance between the center point of two adjacent cells. After τ_b stabilizes below 10^5 Pa on all cells of the glacier, another year of annual mass balance (negative or positive values) is applied to the surface, slopes and basal shear stresses are recalculated, and mass is again moved by avalanching and ice flow.

The upper portion of Sperry Glacier receives enhanced accumulation due to avalanching from the adjacent cirque wall. This is evident from large avalanche debris piles in this area witnessed every spring. To simulate this avalanching, cells with slopes greater than 30° and ice thickness less than 10 m pass their mass accumulation downslope with each annual time step. The 10 m ice thickness cutoff is used allow potential ice falls to form on steep slopes.

3.2. Warming scenarios

We modeled two different climate warming scenarios: (1) no temperature change. The initial mass balance curve (which produces an overall negative mass balance of the glacier) is constant during the 21st century; and (2) linear warming rates. The temperature increases each year by a constant amount so that a target temperature is achieved 100 years after 2008. This scenario was run for 1–10 °C/century warming rates at 1 °C intervals thereby producing 10 sub-scenarios. The IPCC Fourth Assessment Report projections show global surface temperature likely increasing 1.1–5.4 °C by the year 2100 for future emission scenarios A1B, A2, and B1 with the best estimate for temperature increase of 2.8 °C, 3.4 °C, and 1.8 °C respectively for the three scenarios. Locally, an analysis of downscaled OA-GCM output (Coupled Model Intercomparison Project phase 3) for high elevations in northwest Montana found that under scenario A1B the probability distribution function peaks at 0.28 for an end of century mean temperature increase of 3 °C (Gillan et al., 2010). The span of the 0.20 probabilities for end of century temperature increases is 0.5 °C to 6.4 °C warming, and the 0.10 probabilities have a range of a −0.5 °C cooling to a 7.1 °C warming. Our suite of scenarios therefore spans a wide range of projections and includes the tails of the probability distribution for most projections. Specifically, the A1B projection of 3 °C by 2100 is bracketed by our 3 °C/century and 4 °C/century warming rate scenarios which reach +2.76 °C and +3.68 °C in the year 2100, respectively.

Oerlemans (2001) shows that ELA change can be related to change in the mean free-air temperature by:

$$\Delta \mathrm{ELA} = \frac{1}{\gamma}\Delta T_{\mathrm{fa}}, \tag{2}$$

where γ is the local temperature lapse rate. We use the theoretical average lapse rate value of $\gamma = 0.007$ K/m (Oerlemans, 2001) because reported local lapse rates (Finklin, 1986) are variable and overlap with the theoretical. Using this average value of 0.007 K/m implies that for every Kelvin increase in T_{fa} the ELA rises 143 m. We use this relationship to estimate how various changes in T_{fa} will affect the future volume and area of Sperry Glacier. We note that 21st century climate change in northwest Montana may also involve change in precipitation. Climate models project precipitation change of roughly ±5% for northwest Montana, but projections have low confidence and high variance. We therefore do not address precipitation changes in this paper and our results reflect temperature change only in the absence of substantial precipitation change.

Each modeled climate scenario uses the 2008 glacier geometry, ice volume, and mass balance distribution (described in Section 3.1.2) as initial conditions. All model scenarios were run for a 100-year time period, allowing 2 years for model ramp-up time. We output the geometry, volume, and area of the modeled glacier after each year.

4. Results

The 'no change' scenario offers perspective on future changes if the recent average annual mass balance distribution, which has been negative, were to continue indefinitely. Our radar and GPS measurements show the current ice volume to be ~2.59×10^7 m^3 and the maximum depth to be ~80 m. With no increase in T_{fa} the modeled glacier shows a decrease in volume of about 26% and a decrease in area of 19% by ~2030, implying that the glacier is not in equilibrium with current climate. The glacier then remains stable to the end of the century (Fig. 5A and B). A cross-sectional view (Fig. 6A) shows that under these conditions Sperry Glacier retreats ~200 m by 2030. Although the lower elevation portions of the glacier thins and retreats, the upper elevations (above ~2525 m) remain relatively unchanged from the 2008 glacier. The majority of the ice area lost by 2100 is from

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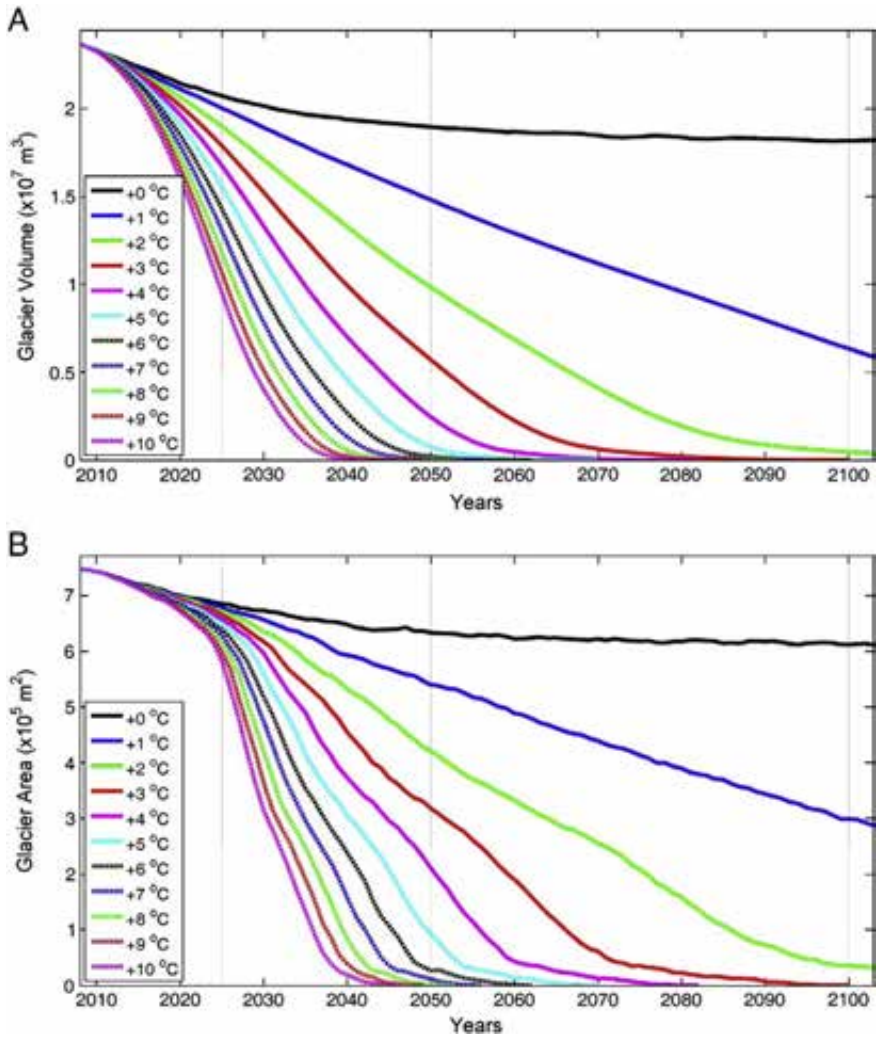

Fig. 5. (A) Total volume vs. time and (B) total area vs. time curves for all model scenarios used in this study. Legend numbers are total degree per century temperature increases. Since modeled temperature increase is simulated by ELA increase (text Eq. (1)) the baseline 'current' temperature is 0.

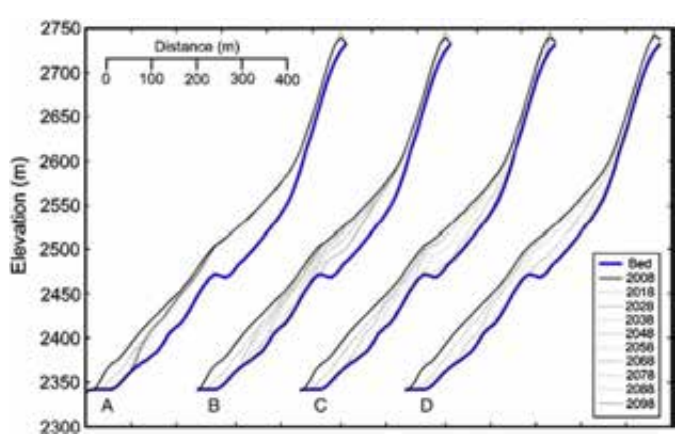

Fig. 6. Elevation profiles for four different modeled scenarios: (A) current B_n, (B) linear increase in temperature of 1 °C per century, (C) linear increase in temperature of 2 °C per century, and (D) linear increase in temperature of 3 °C per century. Each plot shows the bed elevation profile (blue line), the initial (2008) ice surface elevation profile (black line), the ice surface elevation profile in 2098 (red line), and the ice surface elevation profile for every 10 years between 2008 and 2098 (dotted lines). The location of the elevation profile on Sperry Glacier is marked on Fig. 1 (blue dotted line). The profiles are vertically exaggerated by 2.

the lowest elevations where influence from avalanching is minimal or non-existent (Fig. 7B).

With a 1 °C/century warming, the glacier persists in 2100 (Fig. 5A and B) but the area and volume decrease from current values by ~60% and ~75%, respectively. The rate of volume and area reductions are close to linear over the entire modeled time period for the +1 °C/century scenario. Notably, the glacier's rate of area and volume loss tracks the linearly increasing temperature for the entire time span modeled in this scenario, whereas the rate of area and volume loss under warmer scenarios takes 5–10 year to become linear. With a warming of 2 °C/century, the area decreases 95% and the volume is reduced 97% by 2100. Despite dramatic reductions in glacier area (Fig. 6D), the remaining ice is up to 30 m deep. With a warming rate of 3 °C/century the area and volume both decrease by 99.9% by 2100 effectively eliminating the glacier. Hence, the 1 °C/century and 2 °C/century warming rate scenarios do not cause the glacier to disappear, while the 3 °C/century warming rate scenario has it disappearing at about 2100. Since the downscaled AO-GCM prediction of the A1B scenario of 3 °C temperature increase by 2100 is bracketed by our 3 °C/century and 4 °C/century warming rate scenarios our model results conservatively estimate the glacier existing past the year 2080 under the A1B scenario. All warming rate scenarios above 3 °C/century result in the glacier disappearing prior to 2100. Under these scenarios, volume quickly decreases, while area changes take ~10 years to decrease substantially (Fig. 5). As the glacier nears zero

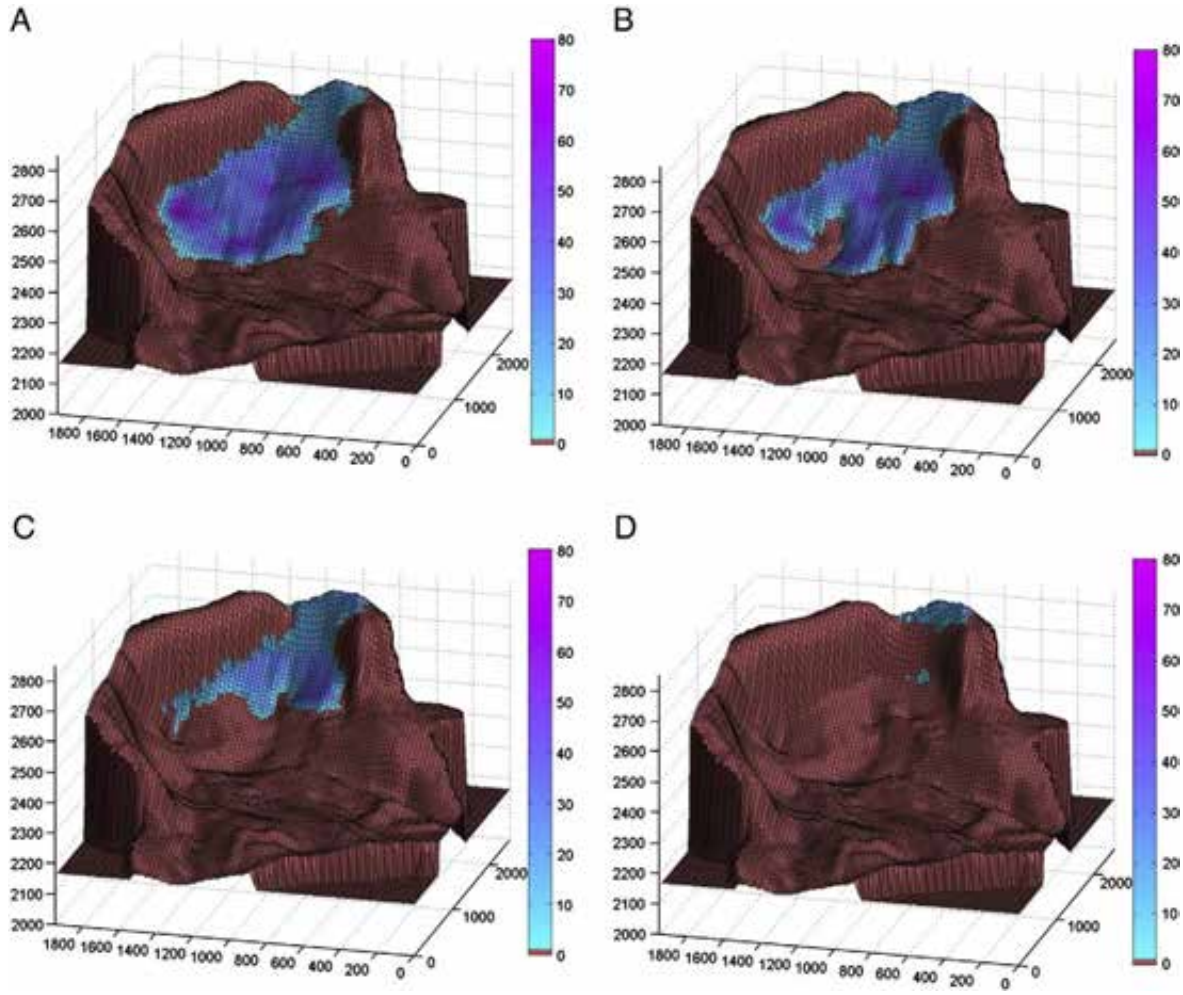

Fig. 7. Model DEM outputs of Sperry Glacier extent and depth including: (A) the interpolated glacier that is the initial condition for all model runs, (B) modeled glacier in the year 2100 under the current B_n scenario, (C) modeled glacier in the year 2100 under the 1 °C per century increase scenario, and (D) modeled glacier in the year 2100 under the 2 °C per century increase scenario. Brown is the current glacier bed (where ablation has occurred) and the surrounding topography, blue to purple is ice depth from 0 m to 80 m, respectively.

volume and area, rates of change slow again, as the only remaining ice occupies the highest, most sheltered part of the cirque wall. Our model shows that Sperry Glacier disappears by 2050 under a warming rate of 9 °C/century or greater (Table 1).

5. Discussion: sensitivity to warming rate

To quantitatively explore the sensitivity of Sperry Glacier to different warming scenarios we computed the ice volume difference between consecutive warming scenarios (i.e., +1 °C/century versus +2 °C/century) over time. At any time t, the volume difference between two consecutive warming scenarios ($\Lambda(t)$), is calculated as:

$$\Lambda(t)|_i = V(t)|_{T=i} - V(t)|_{T=i+1}, \quad (3)$$

where $V(t)|_{T=i}$ is the volume of Sperry Glacier with a warming rate of i °C/century above present temperature (note that i represents temperature rise at a rate of i/century so actual temperatures at any time $t<100$ will be less than i). Hence, $\Lambda(t)$ depicts how records of ice volume for warming scenarios which differ by 1 °C/century diverge

Table 1
Model calculated volume and area of the 11 scenarios included in this study. Each value is given for the years 2025, 2050, and 2100. All model runs assume a starting year of 2008.

Scenario	ΔT_{fa} (°C)	2025 Volume ($\times 10^7$ m^3)	2025 Area ($\times 10^5$ m^2)	2050 Volume ($\times 10^7$ m^3)	2050 Area ($\times 10^5$ m^2)	2100 Volume ($\times 10^7$ m^3)	2100 Area ($\times 10^5$ m^2)
Current B_n	0	2.0714	6.854	1.8954	6.335	1.8166	6.121
	1	2.0009	6.789	1.4799	5.399	0.6352	2.992
	2	1.8961	6.718	0.9832	4.207	0.0474	0.361
	3	1.7863	6.652	0.5700	3.178	0.0000	0.006
	4	1.6718	6.559	0.2453	2.106	0.0000	0.000
Linear rise over 100 years	5	1.5528	6.493	0.0754	0.930	0.0000	0.000
	6	1.4254	6.395	0.0224	0.274	0.0000	0.000
	7	1.3012	6.285	0.0051	0.1203	0.0000	0.000
	8	1.1786	6.160	0.0007	0.0219	0.0000	0.000
	9	1.0615	5.979	0.0000	0.000	0.0000	0.000
	10	0.3997	3.129	0.0000	0.000	0.0000	0.000

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from each other over time. A peak Λ value (max Λ), representing the biggest difference in volume between each 1 °C/century different warming rate, is reached 20 to 100 years in the future (Fig. 8A). The Λ values approach zero as scenario differences either reflect similar glaciers consisting of ice in only the highest elevations of the cirque, or total ablation of the glacier. We did analogous calculations with glacier area.

As expected, larger magnitude increases in warming rate result in larger and earlier reductions in glacier volume and area than do smaller magnitude warming rates. However, our analysis reveals the glacier has variable sensitivity to 1 °C/century differences in warming rate which dependents on the total magnitude of the warming rate, values of max Λ decay exponentially as the total magnitude of the warming rate increases (Fig. 8B and C). For example, max Λ_{volume} at $T=1$–2 is ~5.8 times greater than the max Λ_{volume} at $T=8$–9 and ~2.75 times greater than max Λ_{volume} at $T=4$–8. In other words, scenarios differing by 1 °C/century under low-magnitude warming produce very different ice volumes, but scenarios differing by 1 °C/century under high-magnitude warming result in a similar ice volume at any given time. The decay of max Λ is proportional to the inverse of the total magnitude of the temperature increase. Empirically, we find that:

$$\max \Lambda_{\text{volume}} \big|_{(T_i - T_0)} \propto \frac{1}{(T_i - T_0)^{\beta}}, \tag{4}$$

where, T_0 is the initial (pre-retreat) free air temperature, T_i is the free-air temperature i degrees above T_0, and β is an empirically derived constant that likely represents glacier geometry (i.e., ice depth and hypsometry) and mass balance gradient; for Sperry Glacier $\beta \approx 1.22$ (Fig. 8B, dashed line). The β value is therefore simply a scaling factor used to fit the curvature of the decay function.

Although a decay of max Λ with increasing T stems from the fact that a 1° increase in temperature is a smaller percentage increase of higher temperatures, the max Λ curve (Fig. 8) requires a scaling factor (β) for direct proportionality to $\frac{1}{(T_i - T_0)}$. Two competing processes dictate the growth of Λ over time and therefore the value of max Λ. First, the temperature difference between the two scenarios causes the melt rate of the higher temperature scenario to increase faster than the melt rate of the lower temperature scenario, thus causing Λ to increase over time. The growth rate is not linear, however, because the area of the glacier diminishes over time and there becomes less and less area for melt-rate differences to act on. Second, high elevation accumulation and the resultant mass transfer vary greatly over time between small warming rate scenarios. For example, an area of net accumulation and down-valley ice flow will persist for 73 years longer for a +1 °C/century warming rate than for a +2 °C/century warming rate, and the +2 °C/century warming rate scenario maintains an accumulation area for 25 years longer than a +3 °C/century warming rate scenario. For larger warming rates, however, accumulation and mass transfer processes do not vary significantly between scenarios because the ELA rises above the basin in a short time window (16 years between +6 °C/century and +10 °C/century warming rate scenarios). Thus, since there is very little variation in total accumulation under high-magnitude warming scenarios, these scenarios quickly converge to a similar condition where a nearly stagnate block of ice melts away. In contrast, because there is a large difference in total accumulation between different low magnitude warming scenarios, these scenarios have greater divergence of glacier area and volume adjustments over time.

Because future climate warming will likely have some degree of spatial variability (Shindell and Faluvegi, 2009), the glacier response throughout Glacier National Park could reflect this variability, depending upon the magnitude of warming. If warming is severe we could see little to no regional variability of glacier response with all

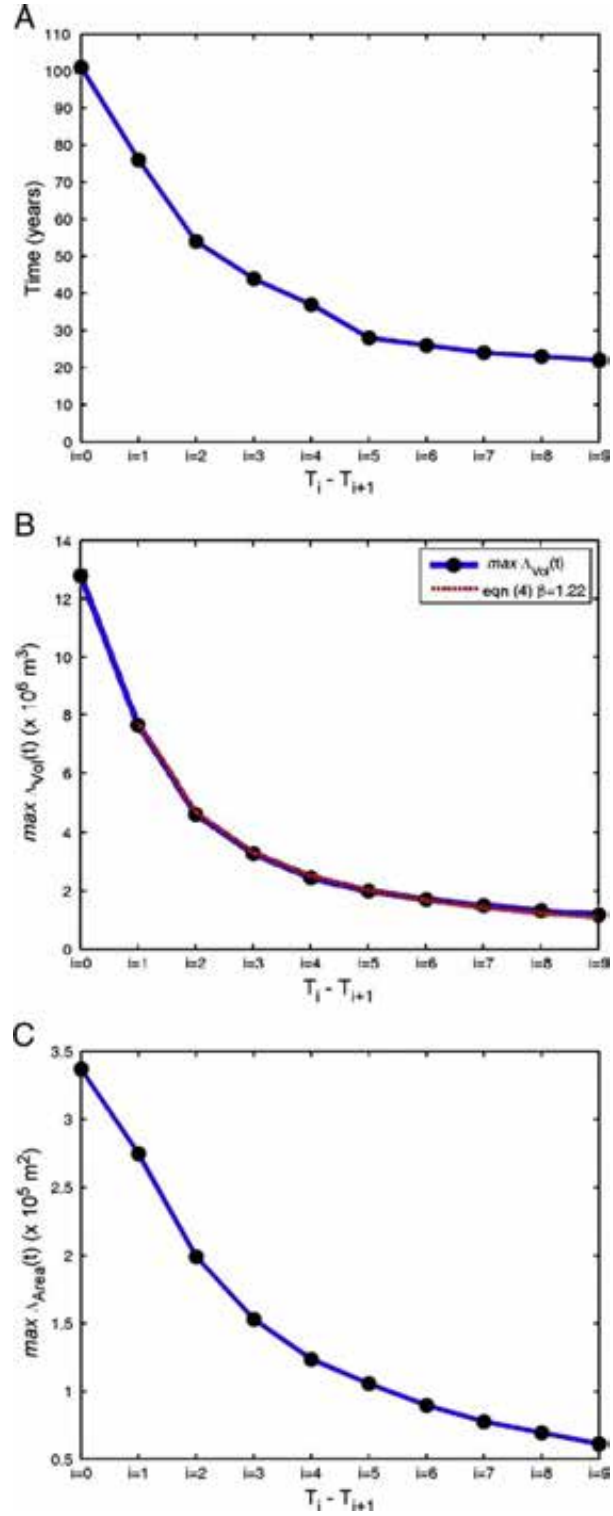

Fig. 8. Maximum value of the difference in ice volume (B) and area (C) between modeled scenarios differing by 1 °C and the time that the maximum volume difference occurs (A). The values of i represent the magnitude of the lower of the two temperature change scenarios being compared. For example, $i=1$ is the difference between the volume of the 1 °C per century linear temperature increase minus the volume of the 2 °C per century linear temperature increase at time t. Note that the $i=0$ point is maximum volume difference between a constant temperature model and a linearly increasing model, all other max Λ points show the relationship between 2 increasing temperature scenarios. Values on the x-axis are denoted by the i values (described in the text and in caption of Fig. 8). The red dotted line in B is the empirical fit to the max Λ_{volume} values (Eq. (4) in the text). Notice that the fit does not relate to the $i=0$ point because Λ is still increasing at 100 years thus the max Λ value is not representative of the value of the models were run for a much longer period.

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glaciers undergoing similar reductions in area and volume. However, if warming is slight, then the minor temperature variations between basins could lead to large regional variations in glacier area and volume changes. For Sperry Glacier, the threshold between the two modes of behavior is a warming rate on the order of 4–5 °C/century.

6. Conclusions

Unless the ELA rises above the highest elevation in the Sperry Glacier basin (~2800 m), there will be net annual accumulation at high elevations and the glacier will never totally disappear. Based on Eq. (2), a 2 °C increase in temperature is required to move the ELA to 2856 m elevation. The most probable projection based on downscaled OA-GCM output using the IPCC (2007) A1B scenario is ~3 °C warming in Northwest Montana by 2100. Our modeling work suggests that under these conditions the glacier will persist through at least 2080. Even for an extreme warming trajectory of 10 °C/century, the modeled glacier exists for another four decades. These results demonstrate the shortcomings of future projections of glacier change based on extrapolation of historical retreat rates.

Under scenarios of a warming climate, larger summer heat input causes greater ablation rates of cirque glaciers. If this greater ablation rate is not balanced by increased accumulation and mass transfer, cirque glaciers will lose mass. Global mean temperature rise has not been spatially homogenous nor is it expected to be in the future, particularly in mountain regions. Our modeling has shown that area and volume changes of Sperry Glacier are more sensitive to minor variations in temperature under low magnitude warming than high-magnitude warming. This has relevance for interpreting ongoing change and anticipating future change to small glaciers in a spatially heterogeneously warming climate.

Acknowledgements

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Projected deglaciation of western Canada in the twenty-first century

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Retreat of mountain glaciers is a significant contributor to sea-level rise and a potential threat to human populations through impacts on water availability and regional hydrology. Like most of Earth's mountain glaciers, those in western North America are experiencing rapid mass loss[1,2]. Projections of future large-scale mass change are based on surface mass balance models that are open to criticism, because they ignore or greatly simplify glacier physics. Here we use a high-resolution regional glaciation model, developed by coupling physics-based ice dynamics with a surface mass balance model, to project the fate of glaciers in western Canada. We use twenty-first-century climate scenarios from an ensemble of global climate models in our simulations; the results indicate that by 2100, the volume of glacier ice in western Canada will shrink by 70 ± 10% relative to 2005. According to our simulations, few glaciers will remain in the Interior and Rockies regions, but maritime glaciers, in particular those in northwestern British Columbia, will survive in a diminished state. We project the maximum rate of ice volume loss, corresponding to peak input of deglacial meltwater to streams and rivers, to occur around 2020–2040. Potential implications include impacts on aquatic ecosystems, agriculture, forestry, alpine tourism and water quality.

Recent global-scale estimates using simple models (for example, refs 3–6) indicate that mountain glaciers could raise sea level by 0.39 m by 2100 (ref. 7). At regional-to-local scales efforts to project glacier mass changes have varied from models that apply glacier dynamics configured for single ice masses (for example, refs 8,9) to those with greater geographical extent that rely on empirical scaling[10,11], scaling in combination with a low-order treatment of ice dynamics[12–14] or sub-grid parameterizations[15]. At these spatial scales the main effects of deglaciation are associated with changes in the hydrologic cycle[16,17] and consequent impacts on water availability, aquatic habitat, hydroelectric power generation, recreation and tourism.

Projections of glacier surface mass balance (accumulation and ablation) can reveal the ultimate fate of glaciers, but they lack information on rates of change of thickness and extent. Glaciers individually respond to changes in the surface mass balance field and may survive an adverse climate by stabilizing at a higher elevation. This stabilization due to changes in glacier hypsometry (ice area altitude distribution) has been represented through scaling empiricisms in all current models of glacier evolution on regional and global scales[5,6,8,15]. A common feature of these models is that they lack a physics-based treatment of glacier dynamics. The central contribution of our study is thus to simulate the changes in ice thickness and extent over a large region using a high-resolution model of glacier dynamics, which yields year-to-year changes in ice area and volume for the entire study region.

Our study area is Alberta and British Columbia (BC) in western North America (Fig. 1), where glaciers account for an estimated area of 26,700 km^2 (ref. 18) and volume of 2,980 km^3 (ref. 19). The geographical scale is comparable to that of other glacierized mountain regions, such as South America (∼31,900 km^2; ref. 7), the Himalaya and Karakoram (∼22,800 km^2 and ∼18,000 km^2; refs 16,20) and Tien Shan (∼16,400 km^2; ref. 21), where declining glacier melt will impact populations. In this study we project the evolution of regionally resolved glaciers from the present to 2100, using a regional glaciation model (RGM; Methods and Supplementary Sections 1 and 2): a high-resolution (200 m) glacier surface mass balance model coupled to a physics-based model of glacier dynamics. Projections are cast in the modelling framework of the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5; ref. 7) and use climate projections from six well-performing General Circulation Models (GCMs; refs 22,23) forced by the four AR5 emissions scenarios. These scenarios, referred to as representative concentration pathways (RCPs), are labelled RCP2.6, RCP4.5, RCP6.0 and RCP8.5, where the numbers indicate the increase in radiative forcing (W m^{-2}) by 2100 relative to pre-industrial values.

Model skill can be assessed by comparing ice hypsometry from a 2005 inventory with modelled results from the same year (Fig. 2), as well as by comparing the number and area of observed and modelled ice masses (ref. 18 and Supplementary Table 3). The model is spun up from an ice-free state at year 0 to reach a quasi-steady state at 1901; subsequently, historical (1902–1979) and reanalysis (1980–2008) climate data are used (Methods and Supplementary Section 2.1). A comparison between spin-ups using steady and stochastic forcing confirms that by 1980 both procedures lead to the same result. Applying the observations of ice extent to a digital elevation model (DEM; Supplementary Section 1) together with an estimate of subglacial topography[19] allows modelled and estimated volumes to be compared. The area comparisons show fractional errors of +17.8% for the Coast, −3.6% for the Interior, −2.9% for the Rockies and +14.1% for All. The fractional discrepancy between modelled and estimated ice volume (Supplementary Table 3) can be large (+60.7% for All), but the influence of these errors on

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Figure 1 Study region and subregions in the Canadian Cordillera of western Canada. Present-day (2005) glacier extent is indicated in white. The yellow rectangle indicates the location of Columbia Reach drainage basin. Inset: Study region (black rectangle) within northwestern North America.

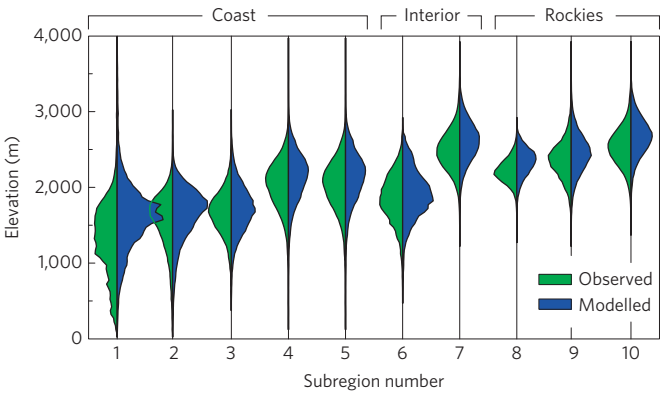

Figure 2 Comparisons of observed and modelled ice hypsometry for reference year 2005. For each of the ten subregions, pairs of bell-shaped curves show the distribution of ice area (normalized to the largest observed area) with elevation for the observed (green) and modelled (blue) ice extent.

normalized projections of area and volume (Fig. 3) is surprisingly small (Supplementary Section 6 and Figs 41 and 44).

Large-scale projections of the model (Fig. 3) are summarized for the Coast, Interior, Rockies and All regions. Glaciers of the Coast region are most resistant to climate change. For these glaciers, depending on the scenario, the ensemble means indicate that, relative to 2005, 75 ± 10% of the 2005 ice area and 70 ± 10% of the volume will be lost by 2100 (here and throughout, error ranges are for model mean $\pm 1\sigma$). For the Interior and Rockies regions ice area and volume losses will exceed 90% of the 2005 amounts for all scenarios except RCP2.6. The resistance of Coast glaciers to climate-forced changes in area and volume is associated with subregions 1 (St Elias), 2 (Northern Coast) and 4 (Southern Coast), which have the highest present-day ice content (Supplementary Table 3). The remaining Coast subregions will experience total or near-total losses of ice area and volume. Comparison of area and volume projections for all GCMs and scenarios revealed that the MIROC-ESM GCM (Supplementary Table 1) most frequently represented the median member of the GCM ensemble. To examine the detailed spatio-temporal character of the model projection, we therefore identified six focus sites and extracted projection modelling time snapshots for the MIROC-ESM projections. The message that the magnitude of deglaciation will be significant does not differ from that of Fig. 3, but the visual consequences of ice loss are emphasized (Supplementary Figs 27–32).

The potential sea-level rise from glacier loss in the study region (6.3 ± 0.6 mm; ref. 19) is modest, but the hydrologic implications of the projected loss are substantial. As an example, the Columbia River, which flows from its headwaters in Interior BC to the Pacific Coast of Washington and Oregon, yields the largest hydroelectric production of any river in North America. The hydroelectric generating capacity of the Canadian headwaters exceeds 5 GW (ref. 24). In BC, the Columbia Reach drainage basin (Fig. 4a) is the most intensely glacierized part of the Columbia River Basin and thus the most susceptible to changes in ice cover. The main influence of glacier runoff in the Columbia River Basin is to maintain stream flow, which contributes water to the Mica Reservoir for hydroelectric power generation (Fig. 4a), and to regulate water temperature through summer months[25,26]. The Columbia River Treaty between Canada and the USA, signed in 1964 and renegotiable from 2024 onwards, provides a detailed framework for cooperation on hydroelectric power generation and flood control. Climate-forced changes in water availability will redistribute costs and benefits between the treaty partners.

The observed (Fig. 4a) and the modelled (Fig. 4b) Columbia Reach ice cover for 2005 broadly agree with the observed and modelled area (733 km^2 and 666 km^2) and volume (44 km^3 and 36 km^3). Widespread glacier loss occurs by 2050 (Fig. 4c), with near-total ice disappearance by 2100 (Fig. 4d) for the MIROC-ESM GCM and the RCP8.5 scenario. Using ice area and volume projection results from the six GCMs (Supplementary Table 1) and four AR5 scenarios, we present time series for the averages and $\pm 1\sigma$ ranges for the multi-model ensemble (Fig. 4e,f). Until mid-century (~2050), the fate of all glaciers in this area is virtually independent of the emission scenario and climate model used for the projections. By the end of the century, however, the ensemble averages range from ~70% (RCP2.6) to ~95% (RCP8.5) reduction of both area and volume relative to 2005 values. The rate of change in ice volume (Supplementary Section 4.5) for each GCM and the RCP2.6 (Fig. 4g) and RCP8.5 (Fig. 4h) scenarios yields the projected changes in meltwater input from glacier ice loss. The graphs clearly show the effect of an unsustainable 'deglaciation discharge dividend' (ref. 27). For the majority of GCMs and scenarios, runoff from glacier wastage is characterized as a well-defined peak in meltwater discharge, having a typical amplitude of ~15 $m^3 s^{-1}$, roughly 3% of the ~500 $m^3 s^{-1}$ annual average discharge of Columbia River at the Mica Dam, followed by decades of declining flow. Our simulated deglaciation discharge (Fig. 4g,h) supplements the annual cycle of glacier storage and melt, and corresponds to annual average rates of mass loss that would mainly occur in summer

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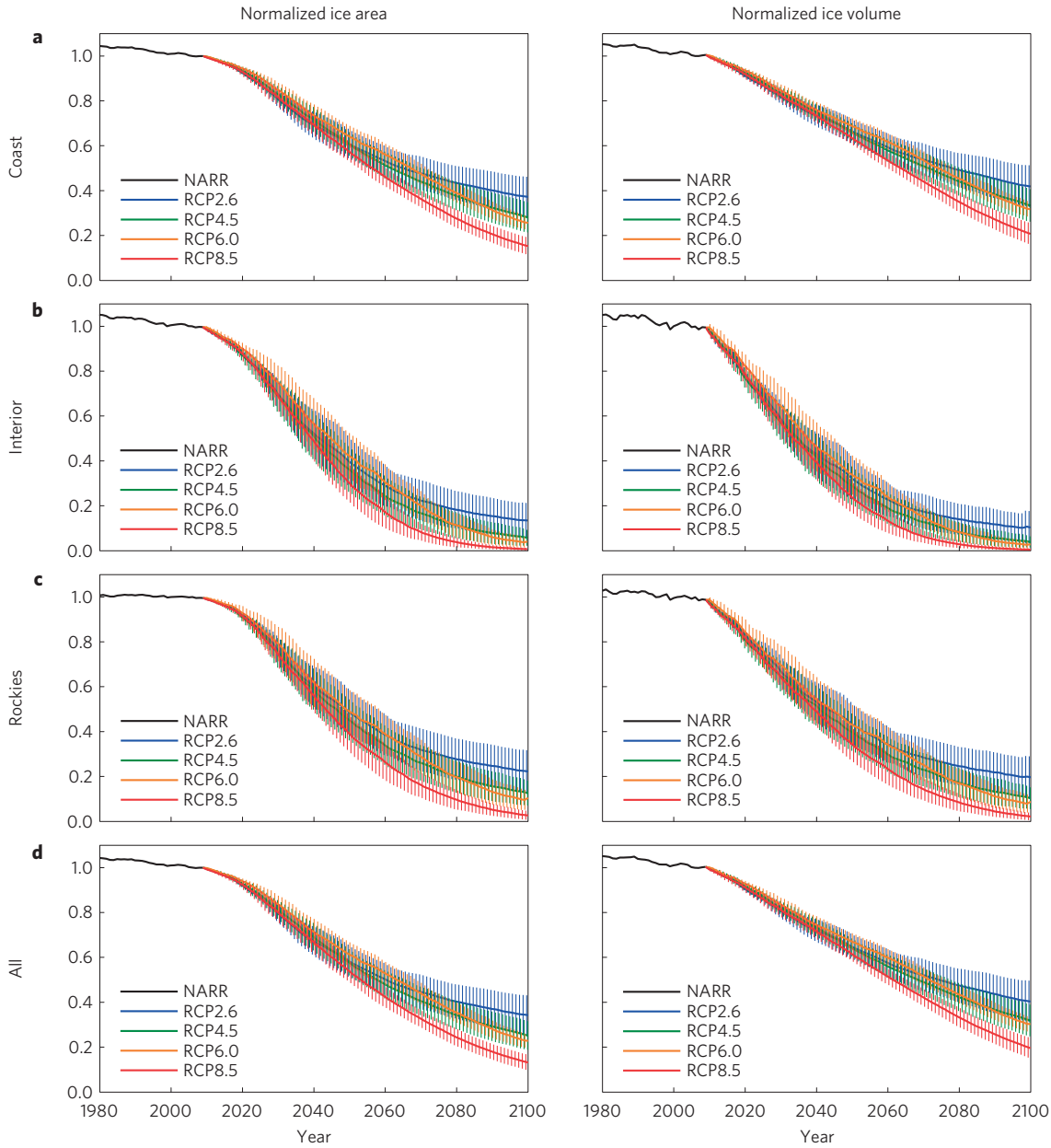

Figure 3 Projected changes for glaciers in the western Canadian study region. a–d, Area (left) and volume (right) are normalized to modelled values for the reference year 2005: projections for Coast glaciers (**a**), Interior glaciers (**b**), Rockies glaciers (**c**) and all glaciers (**d**). The mean (solid curves) and $\pm 1\sigma$ limits (vertical hatching) for the multi-model GCM ensemble are plotted for four different emissions scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5). NARR denotes the North American Regional Reanalysis.

and early fall. Meltwater discharge projections for all GCMs and scenarios and for all regions and subregions, as well as for the Canadian Columbia River Basin, are also calculated (Supplementary Sections 4.5 and 4.7). Most of these runs indicate a clear peak in discharge, in marked contrast to recent runoff projections[28] obtained using a model without ice dynamics that show no peak for western Canada.

Uncertainty in the RGM projections results from the uncertainty concerning which emissions pathway will be followed, from the range of GCM projections of future climate and from shortcomings of the surface mass balance model, the estimated subglacial topography and the ice dynamics model. Uncertainties associated with GCM projections are examined in the AR5 (ref. 7), but for mountainous regions additional uncertainty is contributed by orographic effects on precipitation and temperature[29] (Supplementary Section 2.2). Uncertainties associated with the mass balance model are dominated by the ensemble variability within each scenario rather than by limitations of the model. The error contribution of the ice dynamics model is small relative to that from the surface mass balance treatment (Supplementary Section 9). Our sensitivity analysis (Supplementary Tables 5–10) indicates that projections of ice area and volume have low sensitivity to reasonable parameter assignments for the ice dynamics model but high sensitivity to parameters of the surface mass balance model. Ice dynamics calculations increase the computational demands but do not greatly complicate the projection methodology. Projections performed with and without ice dynamics have been compared (Supplementary Section 7); when ice dynamics are neglected the RGM systematically underestimates ice volume loss at 2100 ($47 \pm 12\%$ loss without

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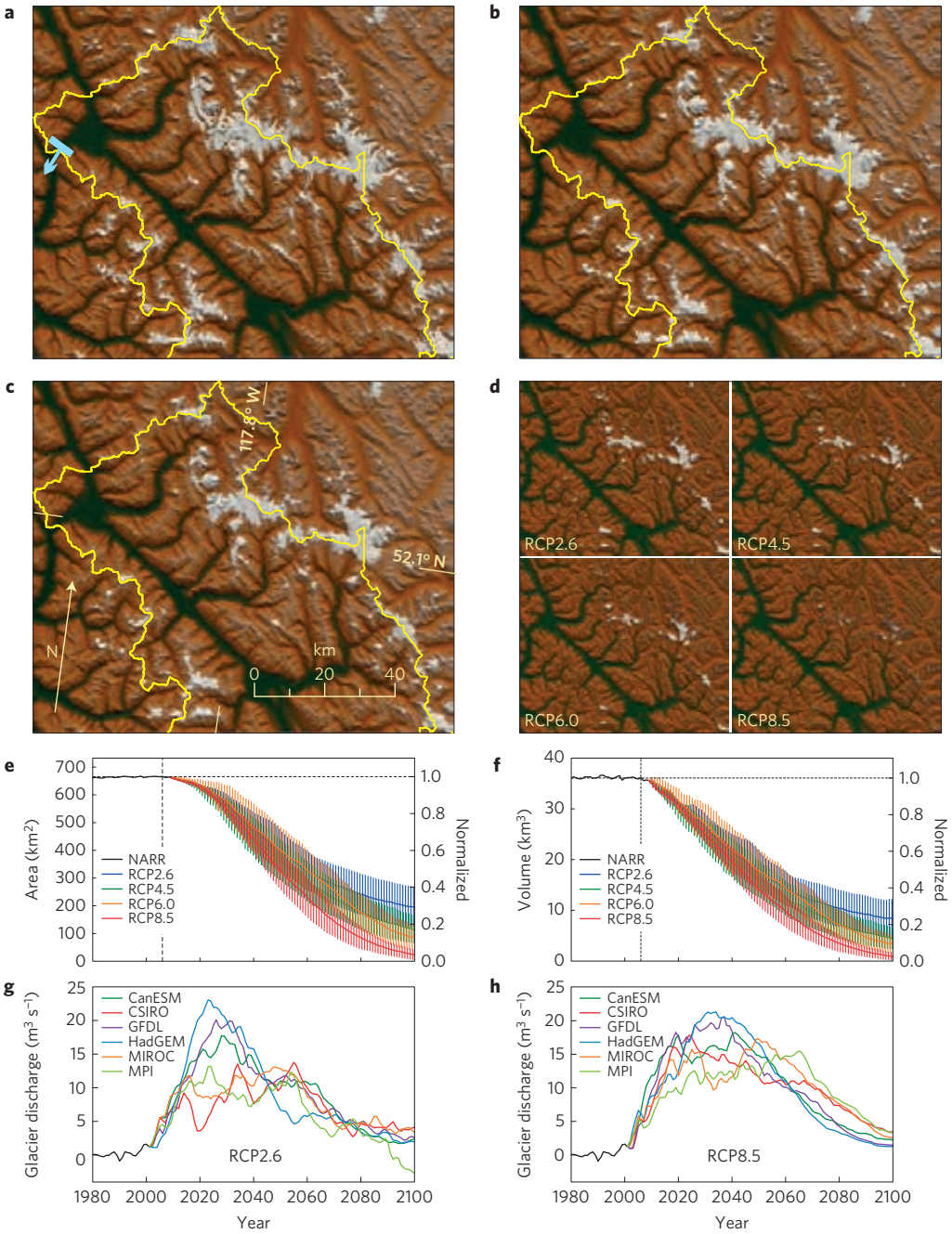

Figure 4 | Projected changes for glaciers in the Columbia Reach drainage basin within the Columbia River Basin of British Columbia. a,**b**, Observed (**a**) and modelled (**b**) glacier extent in the Columbia Reach drainage basin (yellow outline) for the reference year 2005. The Mica hydroelectric dam in the northwest quadrant is indicated by a light blue bar, with an arrow to indicate the water flow direction. **c**, Model projection for 2050 using MIROC-ESM with RCP2.6 forcing. The ice extents for RCP4.5, RCP6.0 and RCP8.5 (not shown) are virtually the same as for RCP2.6. **d**, Model projections for 2100 using MIROC-ESM with RCP2.6, RCP4.5, RCP6.0 and RCP8.5 forcings. **e**, Projected changes in ice area for the drainage basin. **f**, Projected changes in ice volume for the drainage basin. The graphs shown in **e** and **f** are for an ensemble of GCMs and four emissions scenarios; ensemble means are indicated by solid lines and the $\pm 1\sigma$ limits by vertical hatching. The relative changes (right ordinate) are normalized to the modelled values for the 2005 reference year. **g**, Projected changes in mean annual meltwater input from glacier ice loss for the RCP2.6 scenario and an ensemble of GCMs. **h**, Projected changes in mean annual meltwater input from glacier ice loss for the RCP8.5 scenario and an ensemble of GCMs. The maps show the northern half of the drainage basin, which contains ~85% of the present-day ice cover. The time series are the summed contributions for the entire basin.

dynamics and 60 ± 10% with dynamics for 'All' and RCP2.6; Supplementary Fig. 48). Comparisons of observed and modelled ice extents offer a powerful approach to refining surface mass balance fields, but one that is possible only using models that include dynamics. The effects of introducing a mass balance bias correction were carefully examined (Supplementary Section 6). The main challenge remains that of improving the surface mass balance treatment.

In addition to the hydrologic implications of reduced late-summer surface flows in the Columbia Basin, our projected changes of ice cover in western Canada have broader ramifications for aquatic ecosystems, agriculture, forestry, alpine tourism,

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water quality and resource development. Our study departs from previous large-scale projections of glacier response to climate change by including the contribution of ice dynamics and by operating at high spatial resolution despite the large size of the study region. By archiving the deglaciation projections for all the GCMs and scenarios for the entire study region (http://www.unbc.ca/research/supplementary-data-unbc-publications) we open the possibility for a wide range of local- and regional-scale impact studies. With appropriate modifications of the climate projections and surface mass balance models, the present work provides a template for an assessment of future mass change in Earth's other glacierized mountain regions.

Methods

The regional glaciation model (RGM) combines a surface mass balance model that quantifies mass fluxes (accumulation and ablation) at the glacier and land surfaces with an ice dynamics model to simulate ice flow (Supplementary Figs 2 and 3). Both models rely on gridded representations of the present-day surface elevation and ice extent. Data from the 2000 Shuttle Radar Topography Mission (available at http://srtm.csi.cgiar.org) were reprojected and resampled at a resolution of 200 m to obtain a DEM of surface topography; glacier outlines from around 2005 (available at http://www.glims.org/RGI) were used to derive a rasterized and co-registered ice mask. From these and other data, a DEM of the hidden subglacial topography was estimated using an optimization method (Supplementary Section 1.1).

The surface mass balance model calculates ablation by a distributed temperature-index model, accumulation using a temperature threshold to differentiate snow from rain precipitation and refreezing following a parameterized thermodynamic approach (Supplementary Section 2.3). To calibrate the model we force it with downscaled monthly climate fields derived from the North American Regional Reanalysis for 1980–2008 (NARR; ref. 30). NARR temperature and precipitation fields are downscaled from a horizontal resolution of 32 km to 200 m using methods described elsewhere[29]. Model calibration consists of tuning the model parameters to minimize a misfit between modelled and observed glacier mass balances derived from all available *in-situ* and geodetic measurements in the region within the period 1980–2008 (Supplementary Section 2.3). To obtain past and future forcings we take the downscaled NARR monthly averaged temperature and precipitation fields for 1980–2008 to represent the baseline of these fields and superimpose the anomalies from the CRU data set for 1902–1979, and from an ensemble of GCM outputs for 2009–2100 (Supplementary Section 2.5). Forced by these climate fields, the mass balance model yields annual mass balance fields at a resolution of 200 m for 1902–2100 which are then coupled with the glacier dynamics model. The coupling takes into account the feedback mechanisms between glacier mass balance and glacier geometry changes (for example, positive feedback between glacier thinning and mass balance; negative feedback between glacier shrinking and mass balance), while the dynamics model redistributes the mass through ice flow.

The glacier dynamics component of the RGM assumes the shallow-ice approximation and isothermal ice. The model is 2.5D (two-dimensional vertically integrated) with a grid spacing of 200 m. Evolution equations for surface elevation are approximated as finite-difference expressions and solved using a super-implicit numerical scheme and flux-limiters (Supplementary Section 1.2). The ice dynamics model is spun up from an ice-free state at year 0 by randomly selecting the modelled annual mass balance for each year in the range 1902–1931 and applying this forcing from year 0 to 1901, by which time a quasi-steady state ('stochastic equilibrium') is attained. Our simulations start from this modelled 1901 ice configuration, progress through the twentieth century to 2009, and are then projected from 2010 to 2100. Model skill is assessed by comparing the observed ice hypsometry from a 2005 inventory with modelled results for the same year. To improve the model skill, we apply a bias to the surface mass balance field, following similar bias-correction strategies as in other projection studies (for example, refs 3,6). The bias is additive, spatially varying and constant in time (Supplementary Section 2.7). RGM simulations forced with biased and unbiased mass balance fields exhibit differences in the total area and volume of modelled ice, but similar population statistics for glaciers modelled with and without the bias (Supplementary Section 6). Projection results for 2009–2100 for all GCMs and scenarios of our study are archived at http://www.unbc.ca/research/supplementary-data-unbc-publications.

Code availability. The code is not available.

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Author contributions

G.K.C.C., A.H.J. and F.S.A. co-developed the ice flow code used in this study. A.H.J. provided downscaled precipitation fields for the mass balance sub-model as well as numerical insights for the development of the overall model chain. F.S.A. developed the mass balance modelling framework. V.R. performed downscaling of CRU and GCM data, contributed to the development of the bias-correction methods and helped to guide the final write-up. B.M. led the research network, provided essential data sets and guided the final write-up. G.K.C.C. performed the final calculations and wrote the initial versions of the manuscript and supplement.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.K.C.C.

Competing financial interests

The authors declare no competing financial interests.

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AGU PUBLICATIONS

Earth's Future

REVIEW

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Toward mountains without permanent snow and ice

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Key Points:
- Deglaciation of low- to mid-latitude mountain ranges is likely to occur within this century
- Strong impacts on hydrology, erosion rates, sediment and nutrient flux, as well as water quality, aquatic habitat and biotic communities will result
- Far-reaching implications for human adaptation to a world of mountains without permanent snow and ice

Supporting Information:
- Supporting Information S1

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Abstract The cryosphere in mountain regions is rapidly declining, a trend that is expected to accelerate over the next several decades due to anthropogenic climate change. A cascade of effects will result, extending from mountains to lowlands with associated impacts on human livelihood, economy, and ecosystems. With rising air temperatures and increased radiative forcing, glaciers will become smaller and, in some cases, disappear, the area of frozen ground will diminish, the ratio of snow to rainfall will decrease, and the timing and magnitude of both maximum and minimum streamflow will change. These changes will affect erosion rates, sediment, and nutrient flux, and the biogeochemistry of rivers and proglacial lakes, all of which influence water quality, aquatic habitat, and biotic communities. Changes in the length of the growing season will allow low-elevation plants and animals to expand their ranges upward. Slope failures due to thawing alpine permafrost, and outburst floods from glacier- and moraine-dammed lakes will threaten downstream populations. Societies even well beyond the mountains depend on meltwater from glaciers and snow for drinking water supplies, irrigation, mining, hydropower, agriculture, and recreation. Here, we review and, where possible, quantify the impacts of anticipated climate change on the alpine cryosphere, hydrosphere, and biosphere, and consider the implications for adaptation to a future of mountains without permanent snow and ice.

1. Introduction

Mountain environments have great topographic complexity, intertwined with linked physical and biological processes across steep vertical gradients. The mountain cryosphere (snow, ice, and permafrost) plays a critical role in these environments and is an important source of water to downstream regions. Seasonal and longer-term changes in the cryosphere regulate water, nutrient, and sediment supply to mountainous and downstream ecosystems and are crucial for multiple societal needs—agriculture, hydropower generation, drinking water supplies, recreation, and industry. Half of the world's population depends on mountain water, and anticipated future population growth is likely to further increase the pressure on water resources around the globe [*Beniston*, 2003].

Rising air temperatures over the past century have driven a reduction in the area and volume of glaciers, with deglaciation rates in high mountains accelerating in recent decades [*Bolch et al.*, 2012; *Rabatel et al.*, 2013]. A complete loss of glaciers in some low-latitude mountain ranges has already occurred [*Rabatel et al.*, 2013], accompanied by a shorter duration of seasonal snow cover [*Brown and Mote*, 2009] and widespread permafrost thaw [*Haeberli*, 2013]. As concentrations of greenhouse gases in the atmosphere continue to increase, average air temperatures are expected to rise further. Observations and model simulations point to particularly large temperature increases at high elevations, particularly at low latitudes [*Vuille et al.*, 2008;

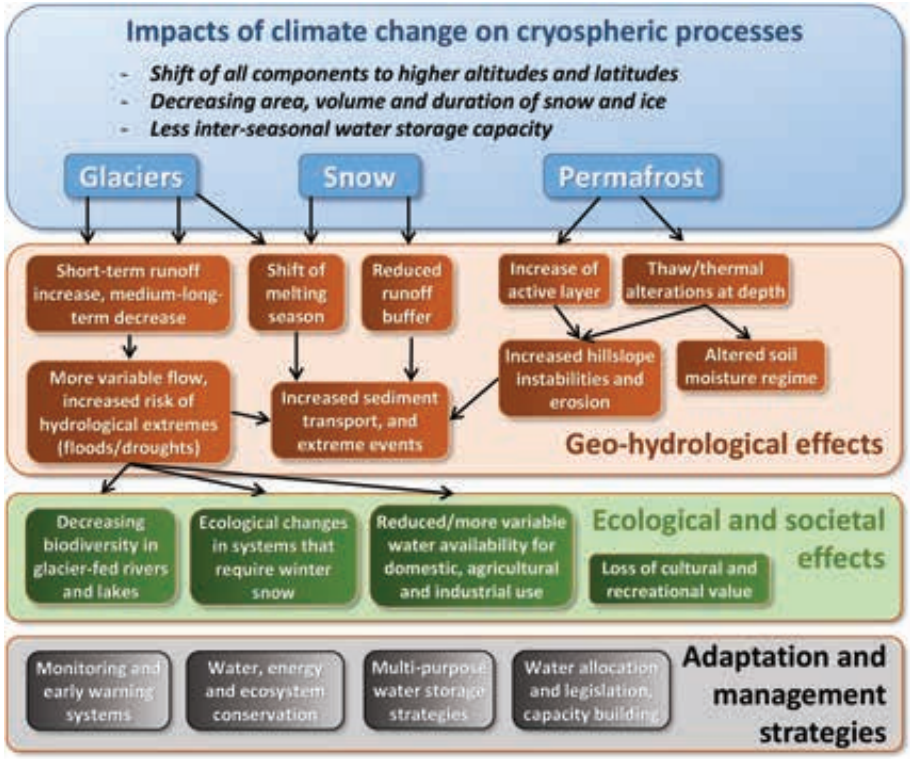

Figure 1. Summary of climate change impacts and process linkages within the mountain cryosphere.

MRI Working Group, 2015]. In addition, local and regional anthropogenic impacts, such as deposition of black carbon on snow and ice and the associated decrease in surface albedo, will have similar consequences [*Ramanathan and Carmichael*, 2008; *Xu et al.*, 2009]. Complex relations among cloud cover, solid and liquid precipitation, surface albedo, and net radiation will lead to further declines in glacier mass balance and the area of snow-covered terrain [*Painter et al.*, 2012]. As a consequence, we are in a transition phase from a world with glacierized mountains to a situation where permanent snow and ice cover is likely to be strongly reduced or even eliminated.

In this review paper, we assess the effect of the future decline of the mountain cryosphere, manifested in a series of cascading impacts on the natural and human systems that the cryosphere supports (Figure 1). Applying a global perspective, we consider the key hydrologic, geomorphologic, and ecological processes in which the mountain cryosphere plays a critical role. We quantify processes and mass fluxes that are presently relatively well understood and point to areas where a lack of quantitative measurements limits our understanding of potential future changes. Our review focuses on recent developments in quantifying present and future glacio-hydrological fluxes, as well as linking them to potential impacts on geomorphology, ecology, and society at the global scale, thus extending the scope of previous comprehensive reviews on this topic [e.g., *Beniston*, 2003; *Barnett et al.*, 2005; *Bolch et al.*, 2012; *Intergovernmental Panel on Climate Change*, 2013] on mountains and climate change.

2. Mass Fluxes Related to the Cryosphere and Mountain Hydrology

Figure 2 provides a schematic view of mountain systems and processes addressed in this paper. We quantify mass fluxes (*F*) and the mass of reservoirs (*M*) related to mountain hydrology at the global scale based on published literature. All fluxes are estimates that are subject to considerable uncertainties, which we do not discuss here. Below we summarize data, methods, and references used to quantify these fluxes.

We evaluate average total precipitation over the Earth's land surface area, except for Antarctica, for the period 1981–2010 based on several different data sets, including those of the Climatic Research Unit (CRU)

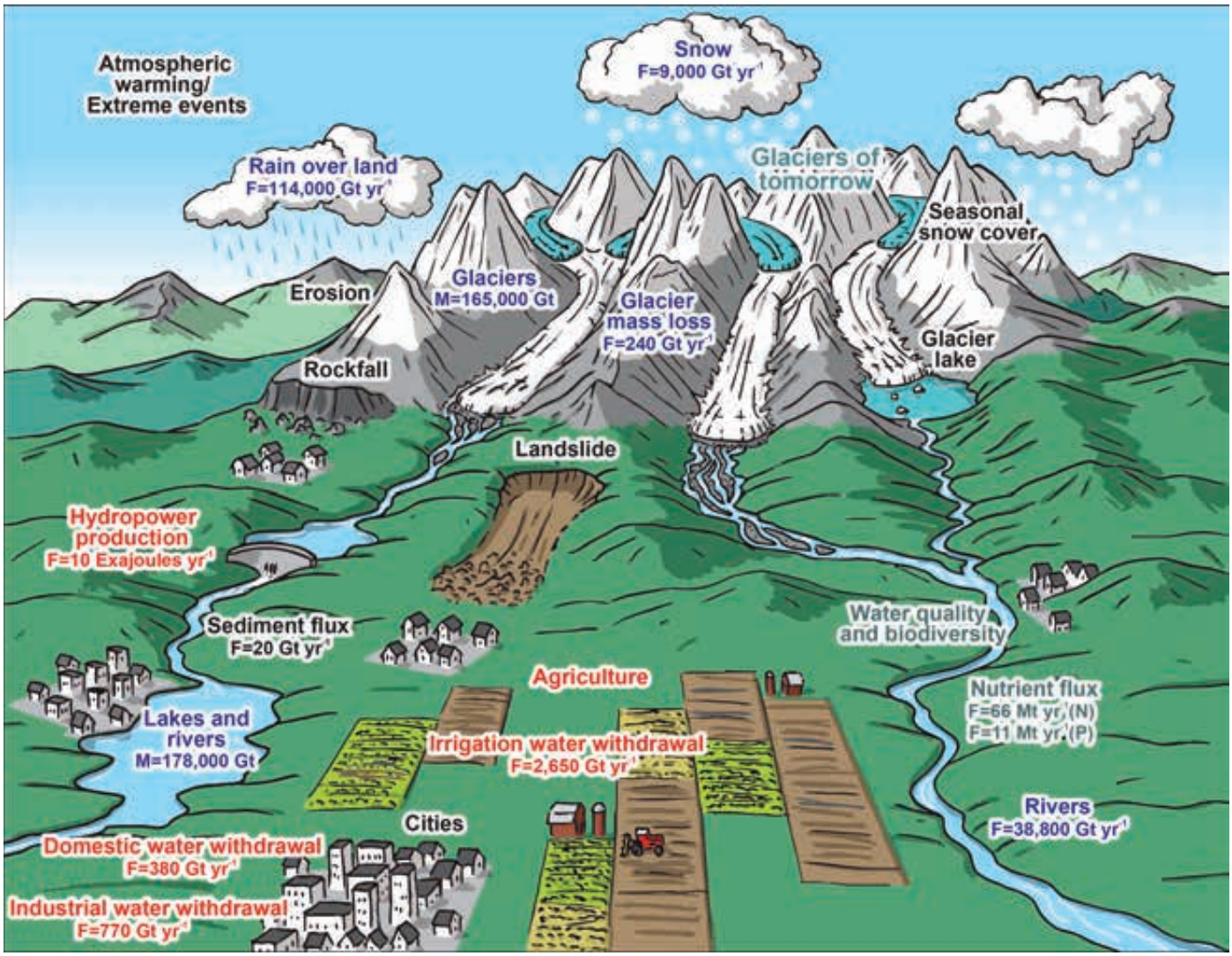

Figure 2. Schematic view of mountain systems and processes addressed in this paper. Estimates of mass fluxes (*F*) and the mass of reservoirs (*M*) refer to the global land surface.

[*Harris et al.*, 2014], the Global Precipitation Climatology Centre [*Schneider et al.*, 2011], and the University of Delaware [*Willmott and Matsuura*, 2001]. These data sets indicate a total precipitation flux over land of $F = 114{,}000\ \mathrm{Gt\ yr^{-1}}$, with a range of $\pm 9{,}000\ \mathrm{Gt\ yr^{-1}}$ among them. Solid and liquid precipitation has been separated using a threshold surface air temperature of 1°C. Temperature data have been provided by the CRU and the University of Delaware data set at monthly resolution and with areal cells of 0.5 × 0.5°, respectively. Snow precipitation over the Earth's land surface area except for Antarctica ($F = 9{,}000 \pm 500\ \mathrm{Gt\ yr^{-1}}$) also refers to the period 1981–2010.

The current mass of the roughly 200,000 glaciers on Earth, excluding the ice sheets in Greenland and Antarctica, is estimated to be in the range of $M = 127{,}000$–$217{,}000$ Gt, based on different studies [*Radić and Hock*, 2010; *Huss and Farinotti*, 2012; *Marzeion et al.*, 2012; *Grinsted*, 2013]. Glacier surfaces used to derive ice volume are provided by the Randolph Glacier Inventory [*Pfeffer et al.*, 2014]. The estimates correspond to about the year 2000. The rate of present glacier mass loss ($F = 240\ \mathrm{Gt\ yr^{-1}}$) refers to the period 2003–2009 [*Gardner et al.*, 2013].

The overall water volume of all lakes and rivers on Earth ($M = 178{,}000$ Gt) is based on a compilation by *Trenberth et al.* [2007]. Total annual runoff of all rivers on Earth into the ocean has been estimated by different authors based on river gauge observations, modeling, hybrid approaches, or the water balance [*Clark*

et al., 2015]. Average values for these approaches range from $F = 31{,}100$ to $F = 41{,}400$ Gt yr^{-1} [*Baumgartner and Reichel*, 1975; *Nijssen et al.*, 2001; *Fekete et al.*, 2002; *Clark et al.*, 2015]. Estimates of the total annual water withdrawal for irrigation range from $F = 2{,}200$ to $F = 3{,}800$ Gt yr^{-1}, mostly based on model-based approaches [e.g., *Oki and Kanae*, 2006; *Wisser et al.*, 2008; *Siebert et al.*, 2010; *Zhou et al.*, 2016]. Overall water withdrawals for domestic ($F = 380$ Gt yr^{-1}) and industrial ($F = 770$ Gt yr^{-1}) uses are based on *Oki and Kanae* [2006]. Total consumptive use of water by humans is estimated as $F = 1{,}380$ Gt yr^{-1} [*Flörke et al.*, 2013; *Zhou et al.*, 2016]. The total energy annually derived from hydropower production ($F = 10$ Exajoules yr^{-1}) is based on estimates made by *Goldemberg* [2000]. *Walling and Webb* [1996] estimated the cumulative annual sediment flux in all rivers globally as $F = 20$ Gt yr^{-1}, although the uncertainties in this estimate are large. Approximate global nutrient fluxes for nitrogen N ($F = 0.066$ Gt yr^{-1}) and for phosphorus P ($F = 0.011$ Gt yr^{-1}) are derived from a transport model by *Seitzinger et al.* [2005].

3. Past and Future Glacier Changes

Mountains accumulate snow, transform snow to firn and ice, and channel and regulate water runoff, which transports sediment and nutrients downstream. Glaciers, snow, and permafrost also store water in regions where other hydrological reservoirs, such as wetlands and aquifers, tend to be limited. A significant amount of water is currently stored in glacier ice in mid- to low-latitude mountain ranges, thus constituting a large hydrological reservoir in regions that shelter the majority of Earth's population (Table S1, Supporting Information). With a seasonal volume of around 9,000 Gt at the global scale (Figure 2), Earth's snow cover is an important element of the cryosphere that is linked to climate via a variety of feedback effects. *Brown and Mote* [2009] analyzed the impacts of climate change on the thickness and duration of snow cover in different mountain regions and found substantial effects on hydrology and ecosystems. In general, snow-to-rain ratios will decrease as air temperatures rise [*Knowles et al.*, 2006], and reductions in snow cover lead to positive feedbacks, enhancing the total radiative forcing of the Earth due to surface albedo changes [*Flanner et al.*, 2011].

Most mountain glaciers worldwide are strongly out of balance with climate and will lose up to one-third of their volume to achieve equilibrium state with current climate [*Mernild et al.*, 2013]. For the period 2003–2009, *Gardner et al.* [2013] estimated the mass loss of glaciers, excluding the ice sheets in Greenland and Antarctica, to be 240 Gt yr^{-1}, corresponding to an ocean water equivalent of 0.72 mm yr^{-1}, or about 30% of observed sea-level rise over this period. Despite the strong ice mass loss across all mountain ranges around the globe, a balanced mass budget has been reported for the early part of this century in some individual regions, for example the Karakoram [*Bolch et al.*, 2012; *Gardelle et al.*, 2012], which is likely due to changes in seasonality, atmospheric circulation, and enhanced winter snow accumulation on some glaciers [*Kapnick et al.*, 2014]. Projections using global circulation models (GCMs) for mountain ranges around the globe indicate major increases in air temperature over the next decades, but an inconsistent pattern for precipitation (Figures S1 and S2). Glacier models forced with GCM-output indicate continued ice loss in all regions [*Marzeion et al.*, 2012; *Giesen and Oerlemans*, 2013; *Radić et al.*, 2014; *Huss and Hock*, 2015]. By the end of the 21st century, relative losses in ice volume of between 30% (Alaska), around 50% (High Mountain Asia), and 80% (European Alps and low latitudes of the South American Andes) are expected, with considerable agreement among different models (Table 1). The total contribution to sea-level rise from mountain glaciers is estimated to be 90–220 mm by 2100 depending on the GCM and the emission scenario considered [*Marzeion et al.*, 2012; *Radić et al.*, 2014; *Huss and Hock*, 2015]. On time scales of a few centuries, an almost complete loss of mountain glaciers is possible if air temperatures continue to rise at current rates [*Levermann et al.*, 2013].

4. Assessing Changes in the Hydrology of Mountain Basins

Runoff from mountainous regions, except for those at low latitudes, is high during summer when other sources of water are often limited in the lowlands [*Barnett et al.*, 2005; *Viviroli et al.*, 2007]. Seasonal water releases from snow, ice, and permafrost are critical for maintaining hydrologic base flow, sediment and nutrient transport, and ecosystem structure and function, thereby providing vital environmental services and resources that are essential for human welfare both within mountains and much farther downstream [*Xu et al.*, 2009; *Immerzeel et al.*, 2010; *Viviroli et al.*, 2011].

Table 1. Calculated Relative Changes in Glacier Ice Volume Between About 2010 and 2100 for Selected Regions Based on Different Studies[a]

	Marzeion et al. [2012]	*Giesen and Oerlemans* [2013]	*Radić et al.* [2014]	*Huss and Hock* [2015]	Overall
Alaska	−28 ± 6%	−35 ± 10%	−25 ± 10%	−32 ± 11%	−30 ± 9%
Western Canada	−64 ± 7%	−45 ± 12%	−74 ± 9%	−76 ± 8%	−65 ± 9%
Scandinavia	−64 ± 10%	−28 ± 8%	−74 ± 24%	−81 ± 14%	−62 ± 14%
European Alps	−76 ± 11%	−88 ± 24%	−97 ± 13%	−77 ± 12%	−84 ± 15%
Caucasus	−53 ± 8%	−73 ± 20%	−75 ± 5%	−70 ± 11%	−68 ± 11%
Central Asia	−53 ± 8%	−54 ± 15%	−54 ± 15%	−54 ± 13%	−54 ± 13%
South Asia West	−39 ± 5%	−61 ± 17%	−41 ± 20%	−51 ± 11%	−48 ± 13%
South Asia East	−55 ± 7%	−88 ± 24%	−54 ± 15%	−66 ± 11%	−66 ± 14%
Sub-tropical Andes	−94 ± 7%	−66 ± 18%	−82 ± 5%	−79 ± 9%	−80 ± 10%

[a]The model results are based on the same emission scenario (Representative Concentration Pathway RCP4.5, except for *Giesen and Oerlemans* [2013], who use the A1B scenario) and the mean of 9–14 global circulation models. The results also are based on identical data on glacier area and distribution, but utilize different approaches to calculate glacier mass balance and retreat. Uncertainties refer to different global circulation models used to drive the glacier models.

To assess the present importance of the cryosphere for water availability in mountain catchments at low to mid-latitudes across all continents, we quantify the contributions of snow water equivalent (SWE) and effective rainfall (rain minus evapotranspiration) based on a combination of global remote-sensing data sets. This assessment is similar to the one made by *Kaser et al.* [2010], but relies on satellite-based observations of the relevant variables rather than climate re-analysis data. For the largest mountain catchments around the planet, we determine the annual totals of snow, glacier mass loss, rain, and evapotranspiration, allowing us to resolve the components of the water balance (Table 2). Data, methods, and uncertainties are described in detail in different studies [e.g., *Tedesco et al.*, 2004; *Bookhagen and Burbank*, 2010; *Bookhagen*, 2016] and are briefly summarized here.

4.1. Snow Water Equivalent (SWE)

Tedesco et al. [2004] provide daily grids of SWE (25 km resolution) based on microwave brightness temperatures using the AMSR-E/Aqua L3 product. Data are available continuously for the period 2002–2011 at the global scale. While there are considerable uncertainties in data derived from passive microwave monitoring at short temporal (i.e., daily) and spatial (at one to several pixels) scales, integration over seasons and entire catchments with drainage areas $>10^3$ km^2 is much more robust [*Smith and Bookhagen*, 2016]. Signal saturation at high snow depths might also affect the results [e.g., *Dong et al.*, 2005], but the effect of these uncertainties on our results at the basin-scale is considered to be limited.

4.2. Rainfall (R)

To estimate the distribution of annual rainfall (liquid precipitation) across all analyzed catchments, we use the Tropical Rainfall Measuring Mission (TRMM) 3B43V7 data set [*Huffman et al.*, 2007]. This data set provides precipitation estimates from multiple satellites, as well as gauge analyses for the period 1998–2012 at a spatial resolution of about 25 km × 25 km (0.25° × 0.25°). TRMM 3B43V7 overestimates single-event rainfall in mountain catchments [e.g., *Bookhagen and Burbank*, 2010; *Wulf et al.*, 2016], but provides reasonable estimates on larger spatial and longer temporal scales [e.g., *Carvalho et al.*, 2012; *Boers et al.*, 2015]. Although the TRMM 3B43V7 data set has been adjusted using precipitation gauges [*Huffman et al.*, 2007], its performance in remote high mountain environments remains difficult to assess because of limited availability of high-quality, long-term rain gauges in these areas.

4.3. Evapotranspiration (ET)

Data on effective evapotranspiration are provided by the MOD16 product [*Mu et al.*, 2007], which is derived from MODIS data at monthly to annual intervals with a spatial resolution of 1 km. The data set spans the

Table 2. Cryospheric, Hydrologic, and Demographic Characteristics of the Major Mountain Basins Analyzed in Figure 3[a]

River Catchment Unit	Basin Area (10^3 km^2)	Population Density (p. km^{-2})	Ice Volume (10^9 m^3)	Glacier Cover (%)	SWE + ΔM_g (10^9 m^3 yr^{-1})	R−ET (10^9 m^3 yr^{-1})	C (%)
Asia							
Yangtze	1,913	248	201	0.14	110	1,265	8
Tarim[(e)]	1,218	9	2,413	2.25	406	131	76
Junggar Basin[(e)]	1,038	11	125	0.28	364	144	72
Tibetan Plateau[(e)]	1,011	1	760	0.85	413	66	86
Ganges	948	399	793	1.30	81	797	9
Indus	859	175	2,559	3.13	262	313	46
Yellow	803	146	11	0.02	61	143	30
Mekong	773	67	29	0.06	29	699	4
Amudarya[(e)]	623	35	1,146	2.38	180	214	46
Brahmaputra	533	109	1,053	3.43	138	594	19
Lake Balkash[(e)]	415	12	157	0.68	189	95	67
Syrdarya[(e)]	326	61	60	0.38	113	92	55
Salween	265	26	62	0.48	47	124	28
Total	10,727	124	9,369	1.03	2,393	4,678	34
South America							
Amazon	5,888	4	62	0.03	4	8,050	0
Orinoco	934	11	0	0.00	0	1,639	0
Altiplano[(e)]	356	7	22	0.18	71	62	53
Central Andes	322	29	49	0.44	12	23	34
Magdalena	259	109	1	0.01	0	403	0
Total	7,760	11	135	0.05	86	10,178	1
North America							
Columbia	653	10	110	0.31	123	284	30
Colorado	628	12	0	0.00	76	86	47
Fraser	232	5	147	1.10	73	194	27
Total	1,513	14	257	0.28	272	564	33
Europe							
Danube	791	103	15	0.04	54	578	9
Rhine	164	298	19	0.21	11	97	10
Rhone	97	99	57	0.89	14	111	11
Po	73	221	16	0.45	18	79	18
Total	1,124	140	107	0.18	97	865	10

[a]Endorheic basins are marked with superscript (e). Population densities for 2000 are based on *Center for International Earth Science Information Network (CIESIN) et al.* [2005]. Snow water equivalent (SWE), glacier mass change (ΔM_g) total annual rainfall (R) and evapotranspiration (ET) are derived from remote sensing data, and the overall relative melt contribution C is calculated using equation (1).

period 2000–2010 and provides reasonable estimates for mountainous regions, for example, the Himalayas [*Bookhagen and Burbank*, 2010; *Wulf et al.*, 2016] and Tibet [*Chen et al.*, 2014]. We note that evapotranspiration is low in vegetation-free, high-elevation regions.

4.4. Glacier Mass Change (ΔM_g)

Annual glacier mass changes for large mountain regions (High Mountain Asia, European Alps, South American Andes, Coast and Rocky Mountains of North America) for the period 2003–2009 have been documented by *Gardner et al.* [2013] based on a combination of different remote sensing and in situ data sets. We have linearly distributed these mass changes over all individual catchments, assuming each glacier will exhibit the same rate of annual thinning as the mountain-range mean. Note that the sum of water issuing from glacier surfaces derives from glacier mass change, snow melt, and rain.

4.5. Contribution of Snow and Ice Melt to Runoff (C)

Combining the above data sets, we quantify to a first order the annual contribution of snow and ice (i.e., melt of the seasonal snow and annual glacier mass loss) to catchment runoff, defined as the sum of effective rainfall (R−ET) and runoff from seasonal snow and ice melt (SWE + ΔM_g). The relative contribution of the cryosphere to runoff is calculated as:

$$C = \left(\mathrm{SWE} + \Delta M_g\right) / \left(\mathrm{R} - \mathrm{ET} + \mathrm{SWE} + \Delta M_g\right) \tag{1}$$

We assume that all discharge is derived from the four components (SWE, ΔM_g, R, ET).

For the present analysis, we assume that the differences in the time periods covered by the individual data sets are negligible. The assessment is thought to be representative for the first decade of the 21st century. Our analysis does not account for groundwater retrieval [*Andermann et al.*, 2012; *Bookhagen*, 2012] and irrigation, which could cause water losses over large parts of the downstream basins.

Our data indicate that present glacier ice volume at low to mid-latitudes is concentrated in High Mountain Asia with smaller volumes in the European Alps, the Caucasus, the Coast and Rocky Mountains, and the Andes (Figure 3a, Table 2). Our simple method for estimating the cryospheric contribution to runoff in mountain catchments (equation (1)) indicates the importance of melting processes, and hence increased potential impacts of future climate change, in rather dry high-elevation regions. We find snow and ice melt contributions of 50% and more in some large-scale basins of High Mountain Asia, as well as in the Andes

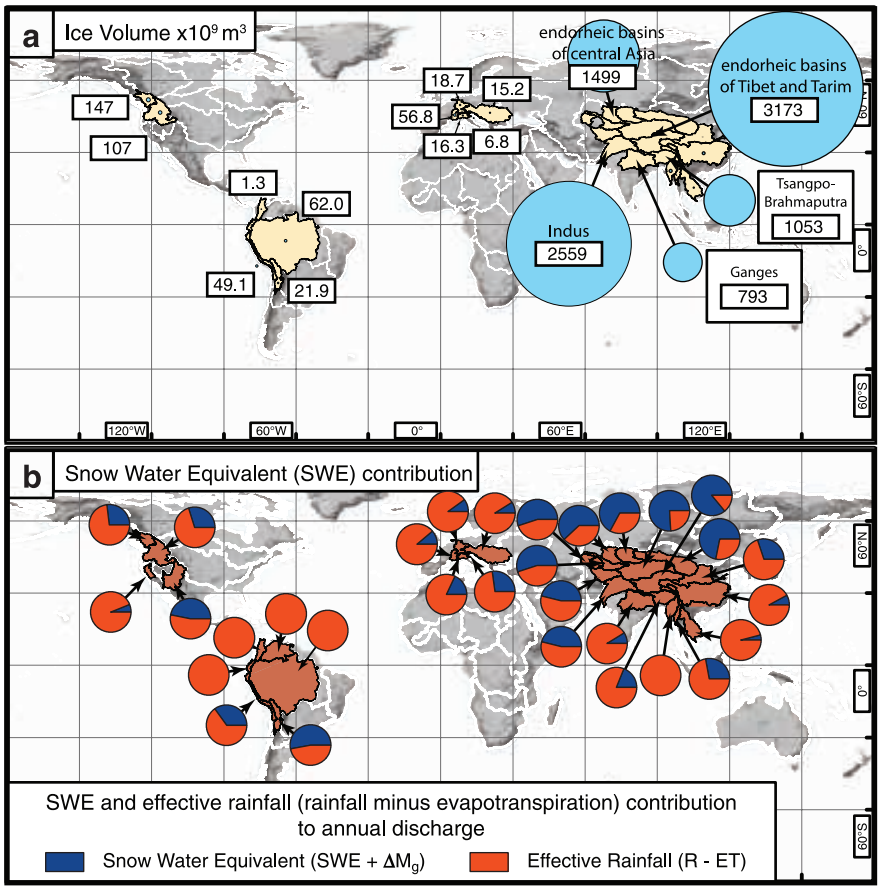

Figure 3. Hydrologic parameters of large mountain catchments. (a) Present-day glacier ice volume within large watersheds in mid- to low-latitude mountain ranges. Blue circles are scaled to ice volume. (b) Relative contributions of snow water equivalent and effective rainfall to total basin runoff. See Table 2 for more detailed information.

(Figure 3b, Table 2). These regions support large populations and also have experienced large population growth over the past decade (e.g., Indus, Table S1). Cryospheric contributions in regions influenced by monsoonal systems are generally small or negligible (e.g., Brahmaputra, Amazonas; Table 2). We note that across most basins the contribution from annual glacier mass loss (ΔM_g) is relatively small (mostly between 0.5% and 5%) compared to the melting of seasonal snow (SWE) (Table S2). However, annual glacier mass loss incompletely describes glacier contributions to runoff because the seasonal hydrological effect of glaciers is dominant [*Radić and Hock*, 2014]. These findings are consistent with earlier studies [e.g., *Schaner et al.*, 2012].

The importance of changes in snow and ice to downstream regions is determined by the hydrological regime of meltwater-fed streams (Figure 3b), ecological systems, and water demand, the last of which is dictated by population density and the importance of runoff to energy, agriculture, and other water-intensive sectors (Tables S1 and S2). Physical understanding and modeling suggest that changes in the type and temporal scale of runoff from glaciers depend on factors such as glacier size, elevation range, and hypsometry, the proportion of glacier cover in a catchment, and the way the glacier melt signal convolves downstream with other hydrological signals (i.e., groundwater, precipitation, and evapotranspiration). In some basins characterized by an arid summer climate, glacier meltwater accounts for up to 50% of melt season discharge [*Kaser et al.*, 2010; *Huss*, 2011; *Schaner et al.*, 2012; *Sorg et al.*, 2012]. Runoff from larger glaciers may increase for a few years to decades during the initial period of negative glacier mass balance, but will inevitably be followed by a decrease in the longer term [*Milner et al.*, 2009; *Mark et al.*, 2015]. Recent studies show that some watersheds with small glaciers in the Andes, North America, and Europe have already reached their "tipping points", also termed "peak water", and show decreasing annual discharge [*Baraer et al.*, 2012; *Frans et al.*, 2016]. Some local and regional-scale modeling studies confirm that runoff from glacierized catchments may increase for a few more decades, albeit with shifts in seasonal regimes [*Farinotti et al.*, 2012; *Immerzeel et al.*, 2013; *Bliss et al.*, 2014; *Lutz et al.*, 2014; *Ragettli et al.*, 2016]. However, a more comprehensive perspective across all glacierized regions of the world is still missing.

4.6. Future Changes in Mountain Hydrology

To investigate future changes in runoff from Earth's glaciers, we rely on model results from the Global Glacier Evolution Model (GloGEM) [*Huss and Hock*, 2015]. The model calculates distributed surface mass balance and glacier geometry changes in response to climatic forcing for each of the roughly 200,000 glaciers on the planet. GloGEM is forced with downscaled monthly air temperature and precipitation provided by 14 GCMs from the Climate Model Intercomparison Project CMIP5 [*Taylor et al.*, 2012]. The glacier model is calibrated using observed glacier mass changes [*Gardner et al.*, 2013] and is validated against in situ data from the World Glacier Monitoring Service [*World Glacier Monitoring Service (WGMS)*, 2012]. Initial ice thickness distribution is updated in annual time steps according to calculated surface mass balance (accumulation plus refreezing minus snow/ice melt). For each of the world's glaciers, GloGEM calculates the altitudinal distribution of surface mass balance at a vertical resolution of 10 m. This also allows the glacier's equilibrium line altitude to be derived now and in future (Figure 4).

Based on GloGEM, we calculate runoff from all presently glacierized surfaces within a drainage basin as the sum of snow/ice melt plus rain minus refreezing (i.e., all water exiting the glacier snout) [see *Radić and Hock*, 2014]. To ensure comparability of runoff volumes over time, we keep the catchment area over which future glacier runoff is evaluated constant during glacier retreat, even if the modeled ice area only covers part of the original basin toward the end of the century. We thus term calculated future runoff stemming from surfaces that are glacierized today as "headwater runoff" (Figure 4).

Figure 4 reveals important differences in the characteristics of glacierized watersheds around the world. Their area-elevation distribution defines ice cover and hence the response times of glaciers and potential future volume losses. In general, we find that headwater runoff continues to increase in the future in catchments with large ice volumes such as in northern North America, parts of the Himalayas, and Central Asia. In contrast, regions with smaller ice volumes at present such the Alps in Europe and the tropical Andes, face a decrease in runoff compared to current conditions. Our results are consistent with earlier findings on the importance of glacier meltwater to runoff [e.g., *Kaser et al.*, 2010; *Schaner et al.*, 2012], but extend the perspective globally and into the future and underline the importance of differences among individual basins. For instance, the contrast between individual basins is particularly strong in High Mountain Asia where the glacier melt season in the densely populated Indus, Ganges, and Brahmaputra basins coincides

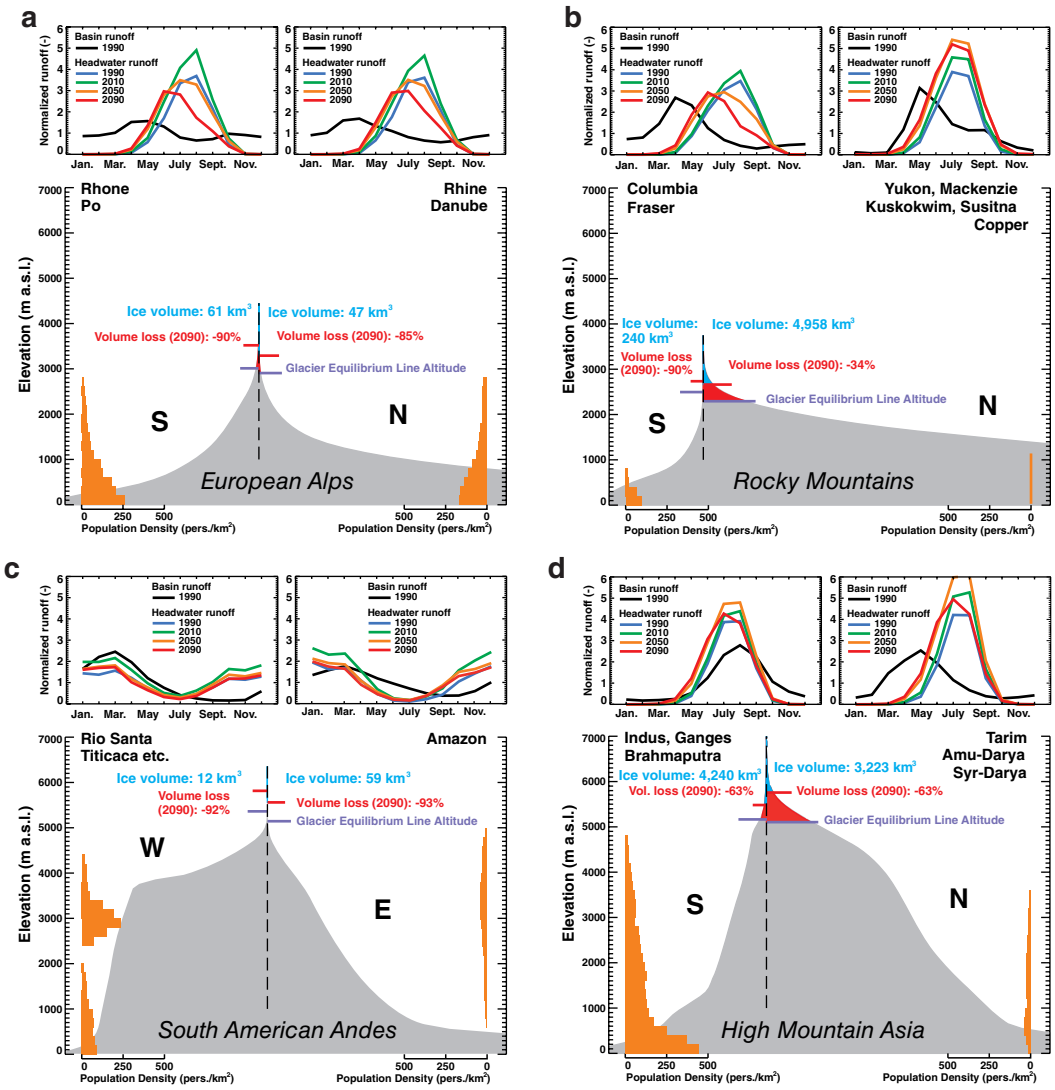

Figure 4. Cumulative land surface hypsometry [*Farr et al.*, 2007] of the world's major glacierized drainage basins: (a) European Alps, (b) western North America, (c) South America, and (d) High Mountain Asia, separated by the main weather divide (e.g., North/South). Present glacier ice volume and basin-averaged glacier equilibrium lines are shown as purple horizontal lines. The present-day (1980–2000) average equilibrium line altitude is based on a glacier area weighted mean. Also shown are modeled future changes in glacier volume and potential loss of glacier area (red), and reductions in equilibrium line altitude (red horizontal lines). Current population density as a function of elevation for each catchment indicates that people living in the lowlands depend on mountain water. Insets show both the observed runoff regime (period 1986–1995) of the respective basins (total monthly discharge normalized with average annual runoff), as well as present-day and future modeled runoff from glacierized areas based on *Huss and Hock* [2015]. Future changes in runoff due to a reduction in snow cover outside glaciers are not included in this analysis.

with high river runoff in the monsoon season, leading to small melt-to-discharge ratios (Figures 3b and 4, Table S2), whereas Central Asian watersheds are characterized by a summer-dry climate and streamflow is substantially enhanced by glacier melt in July and August.

Our global-scale assessment shows the major shifts in seasonal runoff regimes around the world that will result from the effect of reduced snow cover and ice. The results highlight the need to distinguish between the responses of individual basins following a transition toward mountains without permanent snow and ice. Seasonal shifts will be especially important in mid-latitude regions with moderate glacier volumes such as the European Alps and the mountains of western North America and accordingly will have substantial impacts on the hydropower sector, which is important in these regions. Water resource management will also be challenged in regions where glacier melt water is particularly important, notably seasonally dry regions such as parts of the tropical Andes and Central Asia (Figure 4). In addition, the decrease in snow

and ice will likely increase the "flashiness" of mountain streams [*Tang et al.*, 2014]. Runoff will respond more rapidly to rainfall as glacier areas decrease, snow-to-rain ratios tend to become smaller, and the zero-degree line rises [*Knowles et al.*, 2006]. Runoff extremes are likely to occur more frequently in the coming decades, as are long-lasting droughts [*Collins et al.*, 2013]. It is important to note that these hydrological changes will become general in mountain regions, as climate models largely agree that temperature will increase worldwide (Figure S1).

5. Sediment Flux and Hazards in Mountain Areas

Erosion and sediment mobilization, transport, and deposition are fundamental processes in high-mountain regions, with potentially large impacts on society. Here, we review recent progress in understanding the physical processes and related impacts for a future without permanent snow and ice.

Sediment production rates from bedrock, normalized to unit area, are highest in the world's mountains [*Hallet et al.*, 1996]. Much research has been completed on erosion rates in glacierized catchments and on the interplay of climate, glaciers, topography, and tectonics [e.g., *Thomson et al.*, 2010; *Herman et al.*, 2013]. Glacial erosion rates are typically estimated from sediment yield data acquired from rivers and lakes, and range over four orders of magnitude around the world, from <0.1 mm yr^{-1} to about 100 mm yr^{-1} [*Hallet et al.*, 1996; *Koppes and Montgomery*, 2009]. Recently, progress has been made in quantitatively linking glacial erosion rates to glacier sliding velocity [*Herman et al.*, 2015] and to ambient temperature, precipitation, and thus glacier thermal regime [*Koppes et al.*, 2015]. However, there is still limited understanding of the effects of glacier recession on erosion and sediment production. Major gaps in understanding include: (i) the effects of changes in the cryosphere on sediment production on decadal and centennial time scales, as opposed to longer ones and (ii) a comprehensive system perspective that considers the full cryosphere and geomorphic systems. Recent studies that adopt a landscape approach emphasize the importance of the connectivity of different areas within a catchment to decadal-scale changes in sediment production and delivery in attempts to quantify the catchment-scale response to glacier recession [*Lane et al.*, 2016]. Case studies from a large glacierized catchment in the Alps (Monte Rosa, Italy) highlighted that slope instabilities linked to air temperature changes, glacier recession, and permafrost thaw in the late 20th century and the first decade of the 21st century caused an increase in the catchment-scale erosion from 1–2 mm yr^{-1} to about 50 mm yr^{-1} [*Fischer et al.*, 2013]. Important progress has been made in documenting the relations between alpine permafrost degradation and slope destabilization [*Krautblatter et al.*, 2013], but still little is known about their related effects on sediment production and flux at the catchment scale. Anecdotal evidence suggests that cryospheric changes in recent years may be driving geomorphic systems to tipping points, resulting in completely altered mass movement regimes with tremendous impacts on mountain communities, critical energy and transport lines, and hydropower infrastructure [*Huggel et al.*, 2012].

Extreme precipitation and runoff events play an important role in sediment mobilization and transport. High-intensity precipitation, rain-on-snow events, and outburst floods from glacier-, moraine-, and landslide-dammed lakes generate some of the largest hydrologic and sediment-transport events on Earth, with volumes of up to 10^7–10^8 m^3 of sediment delivered in single events and with significant impacts more than 100 km downstream [*Richardson and Reynolds*, 2000; *Korup and Tweed*, 2007]. Glacier lake outburst floods may become more frequent as glaciers thin and recede because new lakes will form and existing ones might grow. Many glacier-dammed lakes will be impacted by mass movements from adjacent destabilized mountain slopes [*Dussaillant et al.*, 2009; *Haeberli et al.*, 2016]. Global and regional climate models indicate that the frequency and intensity of future heavy precipitation events will scale with the rise in global mean temperature and cumulative total greenhouse gas emissions [*Seneviratne et al.*, 2016]. As indicated in the previous section, the synergistic effects of a higher frequency of extreme weather events and a reduced cover of snow and ice to dampen runoff peaks will result in a higher frequency of runoff extremes and thus likely produce higher sediment transport rates and associated impacts on downstream ecosystems and populations. Specifically, there will be substantial effects of enhanced sediment transport and deposition on water quality, aquatic habitat, flooding, infilling of hydropower reservoirs, turbine abrasion, and agricultural and infrastructural development [*Schaefli et al.*, 2007; *Finer and Jenkins*, 2012]. Hydropower infrastructure, especially in headwater regions of the Himalayas, Andes, and Alps, is particularly at risk from increased sediment flux and extreme hydro-geomorphic events [*Schaefli et al.*, 2007; *Wulf et al.*, 2010; *Finer and Jenkins*, 2012].

The magnitude of these impacts is site- and catchment-specific and depends on the resilience and buffering capacities of the system, including the area occupied by glaciers and permafrost, basin hypsometry, groundwater systems, vegetation type and cover, and ecosystem types [*Bruijnzeel et al.*, 2011; *Buytaert et al.*, 2011; *Andermann et al.*, 2012]. The population and infrastructure within the catchment then determine vulnerability and potential damage. However, even within the best-monitored high-mountain catchments, there is still only a rudimentary quantitative understanding of hydro-geomorphic processes and their relation to climate change over relevant spatial and temporal scales. Yet, there is sufficient understanding and evidence to suggest that sediment processes need to be more strongly considered in water resource research and management in deglaciating mountain regions.

6. Aquatic and Terrestrial Ecology

A few organisms, mainly algae and microbes, live in snow and ice [*Anesio and Laybourn-Parry*, 2012]. Many more rely indirectly on the presence of snow and ice, and on their melt. Consequently, aquatic and terrestrial biological communities and processes in mountains are profoundly affected by climatic change, both related and unrelated to changes in the cryosphere.

Numerous studies have demonstrated upward shifts of species and communities in mountains [*Lenoir et al.*, 2008; *Chen et al.*, 2011; *Telwala et al.*, 2013]. Data from the extensive network of monitoring sites covered by the GLobal Observation Research Initiative in Alpine environments (GLORIA) have revealed an increase in the abundance of thermophilic (warm-adapted) plant species at high elevations and an upward shift of 2.5–2.7 m in the distribution limits of species from 2001 to 2008 [*Gottfried et al.*, 2012; *Pauli et al.*, 2012]. In the same period, mean species richness increased by a factor of 3.9 on boreal-temperate mountains, while it decreased by 1.4 on Mediterranean mountains, probably due to climatically driven reduced water availability in Southern Europe [*Gottfried et al.*, 2012; *Pauli et al.*, 2012]. A meta-analysis of worldwide treeline data shows that in 52% of sites, the treeline has been advancing uphill while only 1% reported treeline recession [*Harsch et al.*, 2009]. Warming conditions and advancing plant communities are reducing high alpine habitats and thus space for specialized high alpine species [*La Sorte and Jetz*, 2010; *Dirnbörk et al.*, 2011]. However, climate-mediated range shifts are not necessarily related to changes in the cryosphere as such; they also happen in areas without glaciers. Studies of the ecological effects of the retreating cryosphere are still relatively few, so our understanding of these effects is far from complete and remains largely qualitative. Some trends, however, are well documented and unequivocal.

Rising air temperatures and the attendant shorter duration of snow cover directly influence the length of the growing season and the phenology of plant production and consumers, and thus the alpine-treeline ecotone [*Gottfried et al.*, 2012]. Higher temperatures also increase above-ground net primary production as long as there is no decrease in soil moisture that mediates soil nitrogen availability [*Berdanier and Klein*, 2011]. However, decreasing snow cover and an earlier growing season also expose wildflowers to frost damage [*Inouye*, 2008]. Early snowmelt decreases the mortality rates of some conifers such as *Pinus cembra*, whereas winter and summer drought reduce growth [*Oberhuber*, 2004]. Earlier loss of snowpack and more summer drought are already affecting tree species such as *Pinus contorta*, and at the same time increasing the risk of infestations by bark beetles [*Coops et al.*, 2010].

Receding glaciers and declining snow cover create new habitats and space that is colonized by early-succession, scree slope, and perennial clonal plants [*Chapin et al.*, 1994; *Cannone et al.*, 2008]. The presence of some keystone plants will be crucial for limiting soil erosion on steep slopes. However, some of these species (e.g., *Festuca valesiaca* in the Caucasus) already cope with dry conditions at their physiological limits [*Caprez et al.*, 2011], and increasing drought might limit the ability of such species to sustain this key ecosystem function [*Loreau et al.*, 2002]. Lack of water also inhibits soil microbial activity, thereby decreasing nutrient availability [*Stark and Firestone*, 1995] and primary production. Changes in the amount and seasonal availability of resources for consumers can potentially lead to mismatches, with cascading effects on food webs [*Miller-Rushing et al.*, 2010]. Initial increases in meltwater may elevate phosphorus and nitrogen inputs to downstream alpine wetlands and floodplains during high flows, enhancing the productivity of terrestrial communities [*Tockner et al.*, 2002].

The mountain cryosphere influences downstream aquatic ecosystems by governing flow regimes, channel stability, sediment concentration, water temperature, and nutrient supply, and is essential for supporting

life during dry periods when snow and ice melt is the main water source. Due to harsh environmental conditions, macroinvertebrate communities in glacier-fed rivers are deterministic and dominated by a few specialized cold-water species close to the glacier [*Milner et al.*, 2001] where they find refuge from competitors [*Lencioni et al.*, 2015]. An increase in glacier meltwater runoff will lead to a colder and harsher aquatic environment, and possibly a downstream displacement of aquatic communities [*Jacobsen et al.*, 2014]. In the long term, however, glacier retreat will result in increases in stream temperatures in meltwater streams; sites that were next to the snout of Swiss glaciers in 1998 were 160–480 m farther away in 2009, and had a 2–4°C higher mean summer stream temperature [*Robinson et al.*, 2014]. The mean August temperature of an Alaskan stream increased from 2 to 18°C during from 1978 to 2003 as a result of the complete disappearance of its feeding glacier [*Brown and Milner*, 2012]. Such streams are quite quickly colonized by aquatic communities adapted to higher water temperatures [*Finn et al.*, 2010; *Robinson et al.*, 2014]; specific sites experience increasing species richness through time, tracking rising water temperature and other changing environmental conditions [*Milner et al.*, 2011].

Few datasets allow direct study of the long-term effects of glacier retreat on ecology in mountain streams [*Finn et al.*, 2010; *Milner et al.*, 2011]. However, "space-for-time" substitutions, a commonly used approach in ecology in which sites covering a gradient in glacier cover are used to predict effects of glacial retreat, point to similar results (Figure 5). They show that the richness of local aquatic macrofauna (alpha diversity) peaks at intermediate levels of glacial runoff [*Jacobsen et al.*, 2012; *Khamis et al.*, 2016]. Furthermore, the reduction and eventual loss of meltwater flow is predicted to: (i) reduce environmental heterogeneity at the watershed level, reducing species turnover among sites (beta diversity) [*Jacobsen et al.*, 2012; *Cauvy-Fraunié et al.*, 2015]; (ii) cause the loss of rare and specialized species from the regional species pool (gamma diversity) [*Jacobsen et al.*, 2012; *Quenta et al.*, 2016]; and (iii) elevated algal and herbivore biomasses, thus shifting ecological structure [*Cauvy-Fraunié et al.*, 2016]. In addition, genetic diversity within individual species decreases in headwater areas as glacier melt diminishes, because with less isolation individuals intermix to a greater degree when mating [*Finn et al.*, 2013]. Reduced meltwater also has been shown to reduce migratory corridors for anadromous fish [*Milner et al.*, 2009]. Finally, a shorter duration of snow cover shifts life cycles. For example, earlier emergence [*Finn and Poff*, 2008] and increased production of stream insects [*Schütz et al.*, 2001] may benefit terrestrial invertebrates, reptiles, and birds.

An earlier onset of melting of lake surface ice will affect the heat content, underwater light climate, temperature regime, oxygen regime, and mixing of lakes [*Melack et al.*, 1997]. Indirectly, changes in melting in the catchment can affect downstream lakes through changes in water level, turbidity, water chemistry,

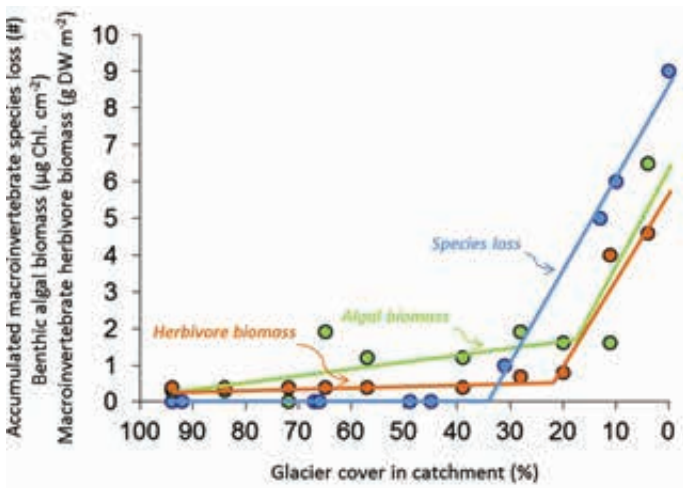

Figure 5. Ecological features of small streams with different percentages of glacier cover in a watershed draining Antisana volcano in the Ecuadorian Andes. *Accumulated species loss* is the number of macroinvertebrate species with a preference for streams influenced by glacier meltwater that are lost from the regional species pool at sites with declining glacier cover. *Algal biomass* is the amount in chlorophyll units (µg cm^{-2}) of algae (periphyton) in stream channels. *Herbivore biomass* is the amount in g dry-weight m^{-2} of the functional feeding group of macroinvertebrates that primarily live on the algae. Data from *Jacobsen et al.* [2012] and *Cauvy-Fraunié et al.* [2016].

input of nutrients and other solutes, and the timing of this input. These changes will individually and synergistically strongly affect benthic and pelagic communities [*Parker et al.*, 2008; *Slemmons et al.*, 2013]. For example, suspended sediment loads from glacier meltwater increase turbidity, which protects zooplankton from ultraviolet B radiation, but also limits light penetration for phytoplankton production and obstructs feeding by zooplankton [*Sommaruga*, 2015]. Due to glacier retreat, proglacial lakes are currently forming at a high rate in most arctic and alpine areas of the world [*Carrivick and Tweed*, 2013]. Typically, these lakes are initially dominated by microbes and devoid of higher life [*Sommaruga and Kandolf*, 2014]. Later, they are colonized by algae, protozoans, and invertebrates, and food webs form [*Sommaruga*, 2015]. As glaciers disappear, or lakes lose connection to them, lake transparency increases, affecting the fitness of species with high demands for phosphorus and increasing ultra-violet radiation and visual predation pressure [*Balseiro et al.*, 2008; *Laspoumaderes et al.*, 2013].

7. Societal Adaptation and Management Strategies

The current transient state of climate, together with future greenhouse gas emissions, will ensure an irreversible loss of glaciers, permafrost, and permanent snow in some mountain ranges, irrespective of future mitigation undertaken by society to moderate climate change. Adaptation to the loss of snow and ice will thus be required in all mountain regions [*Field et al.*, 2012]. Yet, physical, ecological, and socio-economic systems in mountains are multi-faceted, and behave and respond in ways that differ considerably across mountain watersheds [*Das et al.*, 2011]. These systems are typically more complex than can be fully captured by historic observations or simple predictive models. This complexity poses major challenges to adaptation [*Buytaert et al.*, 2010]. On the other hand, general trends in the response of some sub-systems (e.g., the water cycle) to rising air temperatures are relatively well understood, allowing strategies to be developed for the future. A region's sustainability will depend on the capacity to cope with the challenges of climate change, and this will be affected by multiple factors such as the prevailing governance structure, the ecological integrity of the region, and justice accessing local resources [*Schneider et al.*, 2015]. Society should focus on an adaptive governance approach, with continuous learning and flexibility as key aims [*Folke et al.*, 2005]. Information about how systems respond to environmental and human stressors, and the ability to adapt by changing direction are of first-order importance [*Pahl-Wostl*, 2009].

In specific catchments of the European Alps, for example, unprecedented mass wasting related to permafrost degradation has strongly elevated sediment fluxes, requiring a re-evaluation of transport routes and relocation of mountain communities under economic, touristic, energy, and social pressures [*Huggel et al.*, 2012]. In the Andes of Peru, rock and ice avalanches from steep slopes have impacted lakes that formed as glaciers receded, triggering localized disastrous downstream floods and debris flows. At the same time, shrinking glaciers change water availability for local and regional economies during the dry season [*Bury et al.*, 2013]. Emerging adaptation efforts should therefore be focused on water retention measures that address water availability issues and reduce the risk of outburst floods. Nevertheless, actual water usage patterns are more profoundly impacted by societal forces than climatically mediated hydrological supply, underscoring the need to adopt a socio-hydrologic framework to evaluate legal, economic, political, cultural, and social drivers [*Carey et al.*, 2014].

Multiple-use water storage and distribution strategies, for example, systems that meet both irrigation and drinking water needs, will play a key role in future water resource management and in helping communities offset for decreasing storage of water in snow and ice with associated disruptions in the seasonality of flow. Traditionally, water storage infrastructure has been built for single uses (e.g., hydropower, flood control, or irrigation), but changes in seasonal supply and demand will require management for multiple uses. This reassessment requires consideration of the socio-political context with considerable lead-time [*Clarvis et al.*, 2014; *Schneider et al.*, 2015]. Given the importance of temporal and spatial scaling issues and system complexity, the most effective strategies will emerge from regional planning, knowledge sharing, and compromises among the competing water needs of multiple users as well as ecosystem needs. Furthermore, in less developed regions, capacity building, training, and international cooperation continue to be important, and corresponding international environmental policies need to be strengthened.

Limitations to our understanding of mountain environments, as well as the challenges of adaptive management, have implications for future research priorities. There is a compelling need to improve our

understanding of environmental and ecological systems in mountain regions. We have only a limited quantitative comprehension of these systems and their interactions. A stronger knowledge base can better inform sustainable decision-making, which requires a system approach grounded in understanding interactions, impact cascades, and thresholds in the physical and ecological environments. We thus recommend concerted and collaborative efforts to acquire multidisciplinary observations in representative catchments of distinct regions. Ideally, these should be guided by common protocols, similar to the GLORIA network [*Grabherr et al.*, 2000; *Pauli et al.*, 2005; www.gloria.ac.at]. Furthermore, we advocate research programs that involve the full spectrum of stakeholders in order to take into account local experience and views about possible future developments [e.g., *Valdivia et al.*, 2010]. Creating a relevant base of evidence for adaptive governance should foster development of distinct geographic solutions and approaches that may differ among regions because of different social, cultural, and economic interests. A key issue for inhabitants of mountains experiencing climate and other stresses is their resilience in the face of constantly changing conditions and their ability to adapt and maintain basic functions and services [*Folke et al.*, 2010].

Based on our analysis, which has involved both qualitative and quantitative assessments of the directions of change in the mountain cryosphere, it is clear that many important questions remain, requiring more extensive research on specific aspects of the physical, biological, and socio-economic environments of mountain regions. We also recognize major challenges that transcend traditional disciplinary science, requiring further research at the science-society interface.

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Saving the Park's Glaciers

Preserving glaciers for the future.

For generations, Glacier National Park's ice has provided cold water to countless people and wildlife, but that is changing. Protecting the park's glaciers means protecting the tradition of pure mountain water in the American West. Water flowing from the park's dwindling glaciers sustains habitats for countless plants and animals, here and downstream. Protecting these pristine waters also supports agriculture, recreation, and industry across the continent. Though these glaciers can seem far away, what happens here has effects that reach close to home.

We are leading the way.

Glacier National Park is committed to going green and reducing its contribution to a warming climate. Logan Pass, the Apgar Visitor Center, and the Polebridge Ranger Station all obtain power from solar arrays. The park continues to improve its recycling program and reduce the need for single use materials. More efficient LED light bulbs are replacing all the park's old bulbs. Park employees can lower their own carbon footprint by riding the employee shuttle to work everyday The park continues to educate park visitors through interpretive programs, displays, and leading by example.

We need your help.

You can easily reduce your carbon emissions while visiting the park and at home. Start by calculating your carbon footprint. Once you know your carbon footprint you can track your savings and get involved in programs that allow you to buy carbon credits to offset the carbon emissions from your visit. Staying in Kalispell? Take the Eagle Transit shuttle into Apgar for only $5 round trip. Ride one of our free shuttles, bring your bike, or explore on foot. Pull off the road and turn off your car if you are going to stop to take in a view! Plan ahead before you travel and turn off your heat, air conditioning, lights, and unplug any unnecessary appliances before you leave.

Boulder Glacier in 1932 by George Grant, GNP Archives.

Boulder Glacier in 1988 by Jerry DeSanto, K. Ross Toole Archives.

Current Condition of the Park's Ice

The park had 35 named glaciers in 1966. By 2015, nine of those were already inactive. Today, all 35 are melting. Snow avalanches, ice flow dynamics, and variations in ice thickness cause some glaciers to shrink faster than others, but one thing is consistent: all the glaciers have receded since 1966. The black shapes below illustrate the glaciers' 2015 size and the grey shape shows their area 1966. The park has a few more unnamed glaciers that are not included in this chart.

See it for Yourself

Most of the park's glaciers are tucked into shadowy, high elevation, north facing, alcoves and are cloaked by semi-permanent snowfields. Still, a few glaciers can be seen from the road, a few others can be seen from a short hike, and others can be studied up close after a strenuous hike. Late August and early September, when most of the winter's snow has melted away, is the best time to see the glaciers. Visit our website, or ask a ranger, for more information.

Conversation Contents

Interp Projects that we need Nate to assist us with.

Attachments:

/17. Interp Projects that we need Nate to assist us with./2.1 GL-07-400 March 2019 Revisions.pdf
/17. Interp Projects that we need Nate to assist us with./2.2 GL-06-300 March 2019 revised.pdf

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Tue Apr 09 2019 09:41:31 GMT-0600 (MDT)
To:	o Hagen <eric_hagen@nps.gov>
CC:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Interp Projects that we need Nate to assist us with.

Hi Eric

Here is a rundown of some of the projects that we need to have completed prior to the summer. There will be another late summer list as we complete work.

I have project money to pay some of Nate's time this summer.

Two Medicine Campstore
The exhibit in front of the campstore is stuck in the frame. It appears to have been bent by snow or people sitting on it, or both. The panel that is in there now is one of the old porcelain panels. It is not going to be saved, so if it is destroyed in the removal process, no big deal. We have a new panel that was fabricated in town to go there and it is in the Talley Ho Garage.

Running Eagle Fall Nature Trail
There are exhibits that need to be fabricated and put in place. We have the frames but will need the exhibits installed once Nate makes them. They are similar in size and installation to the ones that he did on the Swiftcurrent Nature Trail last year. There are nine of them.

Headquarters Bicycle Map
The exhibit for the end of the bike path (as people enter the housing area) still needs to be fabricated and installed.

Lake McDonald Lodge
Creekside Reading Room panels have been updated and need to be fabricated and installed. We can handle the installation if you can fabricate them. They will need to be on the thicker Sintra. Do you have Sintra or can we just overlay the existing exhibits with the new vinyl?

Apgar Visitor Center
The services panel for the map needs to be installed prior to the start of the season and we need to fabricate replacement panels for the LEEDS exhibits in the plaza. I think there are four but some might be in multiple locations. I will confirm that and let you know. They are 6" x 12"

Apgar Village
We still need to get that triangular exhibit of three panels installed in front of the old visitor center.

Sun Point
There are three exhibits that need to be installed at Sun Point. Two of them have pads already but there is no mechanism to attach them. They will need bolts put in place. The third one will go along the trail a short distance. I'm not sure how that can be attached and I need to chat with you about that. There are three metal exhibit bases in the Tally Ho garage that are to be used for these exhibits. They were powder-coated at the same time as the HAER exhibits and will blend well with the style we are using there. One panel is fabricated and the other two still need to be done.

St. Mary Visitor Center Exhibits
There are four panel around the topo map that need to be recovered with new/updated information. We think you can probably overlay the existing panels with new vinyl. One of them we will need to talk to you about. It has lights embedded in it and we need to change those around. The information that is there is not correct and needs to be changed as soon as possible.

This summer we will be finishing up some other projects and starting to rehab the exhibits in the North Fork. There will also be four or five more exhibits that go on the Sun Point Nature Trail but those are not completed and will be ready at the end of the summer. There are some other assorted projects that remain from past years that need to be wrapped up as well.

--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Tue Apr 09 2019 09:50:56 GMT-0600 (MDT)
To:	"Hayden, William" <bill_hayden@nps.gov>
Subject:	Re: Interp Projects that we need Nate to assist us with.
Attachments:	GL-07-400 March 2019 Revisions.pdf GL-06-300 March 2019 revised.pdf

Here's the final PDFs for the St. Mary exhibits.

Can you review these one more time then we can send them to Eric?

On Tue, Apr 9, 2019 at 9:41 AM Hayden, William <bill_hayden@nps.gov> wrote:

> Hi Eric
>
> Here is a rundown of some of the projects that we need to have completed prior to the

summer. There will be another late summer list as we complete work.

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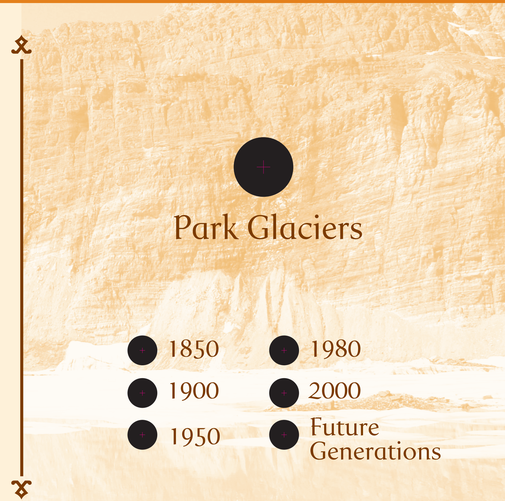
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

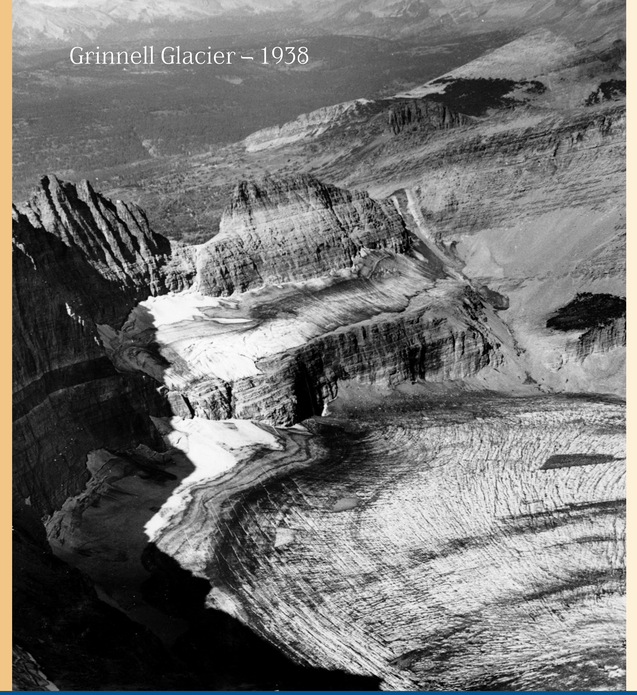
GOODBYE TO THE GLACIERS

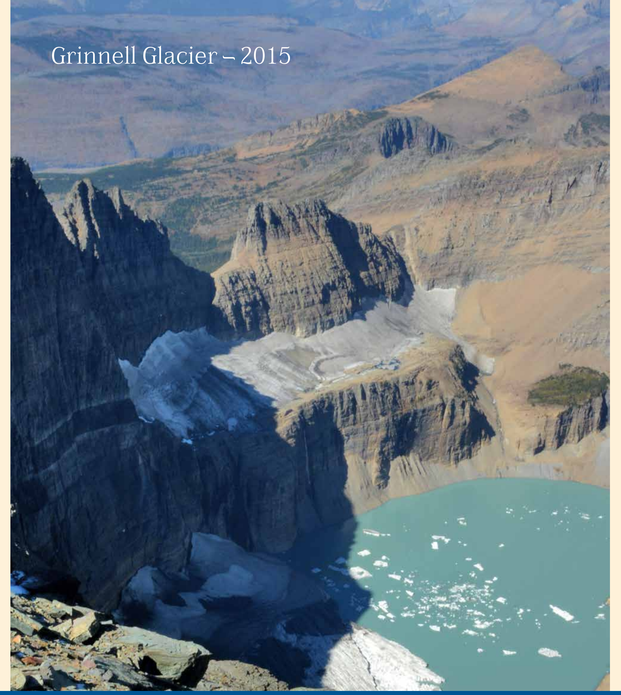
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. Today, they are all rapidly shrinking due to human-caused climate change. When they will completely disappear, however, is difficult to predict.



Glaciers are moving masses of ice. The glaciers that shaped the park were massive. During the Pleistocene—12,000–130,000 years ago—the glaciers covering this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

In 1850 there were about 150 glaciers in the park. In 2015, 26 named glaciers were active in the park.

Some glaciers melt faster than others, but one thing is consistent: all the glaciers are shrinking. Grinnell Glacier, located high in the Many Glacier valley, has lost 45% of its area in recent decades.

GLACIERS ON THE MOVE

Conversation Contents

St. Mary VC Map Pannels

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Sun Mar 31 2019 14:56:35 GMT-0600 (MDT)
To:	Eric Hagen <eric_hagen@nps.gov>
Subject:	St. Mary VC Map Pannels

Hey Eric,

Next time you're in HQ can you swing by and take a look at two exhibit panels from the St. Mary VC that we need to replace and tell me what you think we should do. I should be around and free most days this week.

We have two panels from the VC that have inaccurate information. I've redesigned and updated the information but I'm not sure how we should attach it to the exhibit and I'm hoping you might have an idea.

thanks

-daniel

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

Conversation Contents

Fwd: St Mary text - quick question

"Mckeon, Lisa" <lisa_mckeon@usgs.gov>

From:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Sent:	Wed Mar 20 2019 09:13:25 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Fwd: St Mary text - quick question

Daniel,

Caitlyn makes a good point about the uncertainty. Your text is probably best to use.

Lisa

Lisa McKeon
USGS - Glacier Field Station
PO Box 169
West Glacier MT 59936
406/888-7923 wk
406/253-3223 mobile
lisa_mckeon@usgs.gov

---------- Forwarded message ---------
From: **Florentine, Caitlyn** <cflorentine@usgs.gov>
Date: Wed, Mar 20, 2019 at 9:04 AM
Subject: Re: St Mary text - quick question
To: Mckeon, Lisa <lisa_mckeon@usgs.gov>

Hey Lisa,

Good question. I prefer "future generations" because it honors various uncertainties and caveats, while still being meaningful and connecting landscape change to the lived human experience. Whereas "next few decades" may or may not work, e.g. depending on whether "glacier" indicates body of ice >0.1 sq km or >0.01 sq km, whether "few" indicates 20 or 30 or 40 years, etc.

Cheers,
Caitlyn

On Tue, Mar 19, 2019 at 9:15 AM Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

> What do you think about using the term "next few decades" next to the light where Daniel currently has "future generations"? There are no lights illuminated at that point so it will indicate there will be no glaciers in the park in the next few decades.
>
> *Lisa McKeon*

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--
Caitlyn Florentine, PhD
USGS Northern Rocky Mountain Science Center
215 Mather Drive
West Glacier, MT 59936
cflorentine@usgs.gov
406-888-7924 (office)
303-548-7693 (cell)

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed Mar 20 2019 10:47:20 GMT-0600 (MDT)
To:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Subject:	Re: St Mary text - quick question

Okay great, thanks.

On Wed, Mar 20, 2019 at 8:13 AM Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

Daniel,

Caitlyn makes a good point about the uncertainty. Your text is probably best to use.

Lisa

Lisa McKeon
USGS - Glacier Field Station
PO Box 169
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From: **Florentine, Caitlyn** <cflorentine@usgs.gov>
Date: Wed, Mar 20, 2019 at 9:04 AM
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Cheers,
Caitlyn

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> _____
> *Lisa McKeon*
> *USGS - Glacier Field Station*
> *PO Box 169*
> *West Glacier MT 59936*
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--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Tue Mar 26 2019 12:49:47 GMT-0600 (MDT)
To:	William Hayden <bill_hayden@nps.gov>
Subject:	Fwd: St Mary text - quick question

You weren't on this email where Lisa and Caitlyn decided against "next few decades."

---------- Forwarded message ---------
From: **Mckeon, Lisa** <lisa_mckeon@usgs.gov>
Date: Wed, Mar 20, 2019 at 8:13 AM
Subject: Fwd: St Mary text - quick question

To: Lombardi, Daniel <daniel_lombardi@nps.gov>

Daniel,

Caitlyn makes a good point about the uncertainty. Your text is probably best to use.

Lisa

Lisa McKeon
USGS - Glacier Field Station
PO Box 169
West Glacier MT 59936
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lisa_mckeon@usgs.gov

---------- Forwarded message ---------
From: **Florentine, Caitlyn** <cflorentine@usgs.gov>
Date: Wed, Mar 20, 2019 at 9:04 AM
Subject: Re: St Mary text - quick question
To: Mckeon, Lisa <lisa_mckeon@usgs.gov>

Hey Lisa,

Good question. I prefer "future generations" because it honors various uncertainties and caveats, while still being meaningful and connecting landscape change to the lived human experience. Whereas "next few decades" may or may not work, e.g. depending on whether "glacier" indicates body of ice >0.1 sq km or >0.01 sq km, whether "few" indicates 20 or 30 or 40 years, etc.

Cheers,
Caitlyn

On Tue, Mar 19, 2019 at 9:15 AM Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

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> *Lisa McKeon*
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"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Tue Mar 26 2019 13:03:05 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: St Mary text - quick question

Boooooo

On Tue, Mar 26, 2019 at 12:50 PM Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> You weren't on this email where Lisa and Caitlyn decided against "next few decades."
>
> ---------- Forwarded message ---------
> From: **Mckeon, Lisa** <lisa_mckeon@usgs.gov>
> Date: Wed, Mar 20, 2019 at 8:13 AM
> Subject: Fwd: St Mary text - quick question
> To: Lombardi, Daniel <daniel_lombardi@nps.gov>
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> Subject: Re: St Mary text - quick question
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>
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Cheers,
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--
Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

Conversation Contents

ST MARY VISITOR C... - Made a comment

"Lisa Mckeon (Google Docs)" <comments-noreply@docs.google.com>

From:	"Lisa Mckeon (Google Docs)" <comments-noreply@docs.google.com>
Sent:	Sat Mar 16 2019 09:05:07 GMT-0600 (MDT)
To:	<daniel_lombardi@nps.gov>
Subject:	ST MARY VISITOR C... - Made a comment

Lisa Mckeon replied to a comment in ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

Daniel Lombardi
Made a comment

William Hayden
Made a comment

Lisa Mckeon
Made a comment

Open

Google LLC, 1600 Amphitheatre Parkway, Mountain View, CA 94043, USA

You have received this email because you are a participant in this thread. Change what Google Docs sends you. You can reply to this email to reply to the discussion.

"William Hayden (Google Docs)" <comments-noreply@docs.google.com>

From:	"William Hayden (Google Docs)" <comments-noreply@docs.google.com>
Sent:	Tue Mar 26 2019 10:02:11 GMT-0600 (MDT)
To:	<daniel_lombardi@nps.gov>
Subject:	ST MARY VISITOR C... - Made a comment

William Hayden replied to a comment in ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

Daniel Lombardi
Made a comment

William Hayden
Made a comment

Lisa Mckeon
Made a comment

Daniel Lombardi
Made a comment

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Open

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Conversation Contents

Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Fri Mar 15 2019 13:07:30 GMT-0600 (MDT)
To:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

Nice, made two comments.

On Thu, Mar 14, 2019 at 5:17 PM Daniel Lombardi (via Google Docs) <drive-shares-noreply@google.com> wrote:

> Daniel Lombardi has invited you to **edit** the following document:
>
> ST MARY VISITOR CENTER EXHIBITS ON GLACIERS
>
>
>
> Can you provide feedback to the St. Mary VC exhibits again? I've made changes and I'm looking to start the fabrication process.
>
> Open in Docs
>
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Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

Conversation Contents

Timeline version of goodbye to the glaciers exhibit

Attachments:

/22. Timeline version of goodbye to the glaciers exhibit/1.1 IMG_3868.jpg
/22. Timeline version of goodbye to the glaciers exhibit/2.1 IMG_3868.jpg
/22. Timeline version of goodbye to the glaciers exhibit/3.1 IMG_3868.jpg
/22. Timeline version of goodbye to the glaciers exhibit/4.1 IMG_3868.jpg
/22. Timeline version of goodbye to the glaciers exhibit/5.1 IMG_3868.jpg
/22. Timeline version of goodbye to the glaciers exhibit/6.1 IMG_3868.jpg
/22. Timeline version of goodbye to the glaciers exhibit/7.1 IMG_3868.jpg

"Rademaker, Lee" <lee_rademaker@nps.gov>

From:	"Rademaker, Lee" <lee_rademaker@nps.gov>
Sent:	Thu Feb 28 2019 12:05:10 GMT-0700 (MST)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Timeline version of goodbye to the glaciers exhibit
Attachments:	IMG_3868.jpg

IMG_3868.jpg

Here is a quick drawing of the timeline idea. The lights are black dots along the chart.

Lee Rademaker
Lead Interpreter
Hudson Bay District
Glacier National Park
406-732-7791
Days off: Saturday / Sunday

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent: Thu Feb 28 2019 12:09:30 GMT-0700 (MST)
To: "Rademaker, Lee" <lee_rademaker@nps.gov>
Subject: Re: Timeline version of goodbye to the glaciers exhibit
Attachments: IMG_3868.jpg

So you think we can move the lights?

On Thu, Feb 28, 2019 at 12:05 PM Rademaker, Lee <lee_rademaker@nps.gov> wrote:

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> Days off: Saturday / Sunday

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Rademaker, Lee" <lee_rademaker@nps.gov>

From: "Rademaker, Lee" <lee_rademaker@nps.gov>
Sent: Thu Feb 28 2019 12:19:16 GMT-0700 (MST)
To: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject: Re: Timeline version of goodbye to the glaciers exhibit
Attachments: IMG_3868.jpg

I believe so. It will take a little work to add some extra lengths of wire, but it is low voltage stuff that our electrician (or me) should be able to handle. I'm going to double check this later today.

Lee Rademaker
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Hudson Bay District
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Days off: Saturday / Sunday

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> --
> Daniel Lombardi
> Visual Information Specialist
> Glacier National Park
> 406-888-7933

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu Feb 28 2019 13:23:15 GMT-0700 (MST)
To:	"Rademaker, Lee" <lee_rademaker@nps.gov>
Subject:	Re: Timeline version of goodbye to the glaciers exhibit
Attachments:	IMG_3868.jpg

I like this idea/design.

Bill is telling me we should try and do something as quick and simple as possible.

On Thu, Feb 28, 2019 at 12:19 PM Rademaker, Lee <lee_rademaker@nps.gov> wrote:

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Daniel Lombardi

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Glacier National Park
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"Rademaker, Lee" <lee_rademaker@nps.gov>

From:	"Rademaker, Lee" <lee_rademaker@nps.gov>
Sent:	Thu Feb 28 2019 16:39:38 GMT-0700 (MST)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: Timeline version of goodbye to the glaciers exhibit
Attachments:	IMG_3868.jpg

I am open to doing something quick and simple. But, I will see if Debby wants to talk to Bill about it and let them make the final decision. If they *do* decide to do the timeline idea, the lights are easy to move around and there is enough extra wire to move the lights and button anywhere on that panel. Also, the panel looks pretty easy to remove from the map (just a few screws) but, removing the lights and button will be a little tricky.

Lee Rademaker
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Hudson Bay District
Glacier National Park
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Days off: Saturday / Sunday

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Daniel Lombardi
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406-888-7933

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Fri Mar 01 2019 08:42:23 GMT-0700 (MST)
To:	William Hayden <bill_hayden@nps.gov>
Subject:	Fwd: Timeline version of goodbye to the glaciers exhibit
Attachments:	IMG_3868.jpg

---------- Forwarded message ---------
From: **Rademaker, Lee** <lee_rademaker@nps.gov>
Date: Thu, Feb 28, 2019 at 4:40 PM

Subject: Re: Timeline version of goodbye to the glaciers exhibit
To: Lombardi, Daniel <daniel_lombardi@nps.gov>

I am open to doing something quick and simple. But, I will see if Debby wants to talk to Bill about it and let them make the final decision. If they *do* decide to do the timeline idea, the lights are easy to move around and there is enough extra wire to move the lights and button anywhere on that panel. Also, the panel looks pretty easy to remove from the map (just a few screws) but, removing the lights and button will be a little tricky.

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Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Thu Mar 07 2019 14:02:31 GMT-0700 (MST)
To:	Caitlyn Florentine <cflorentine@usgs.gov>
Subject:	Fwd: Timeline version of goodbye to the glaciers exhibit
Attachments:	IMG_3868.jpg

---------- Forwarded message ---------
From: **Rademaker, Lee** <lee_rademaker@nps.gov>
Date: Thu, Feb 28, 2019 at 12:05 PM
Subject: Timeline version of goodbye to the glaciers exhibit
To: Lombardi, Daniel <daniel_lombardi@nps.gov>

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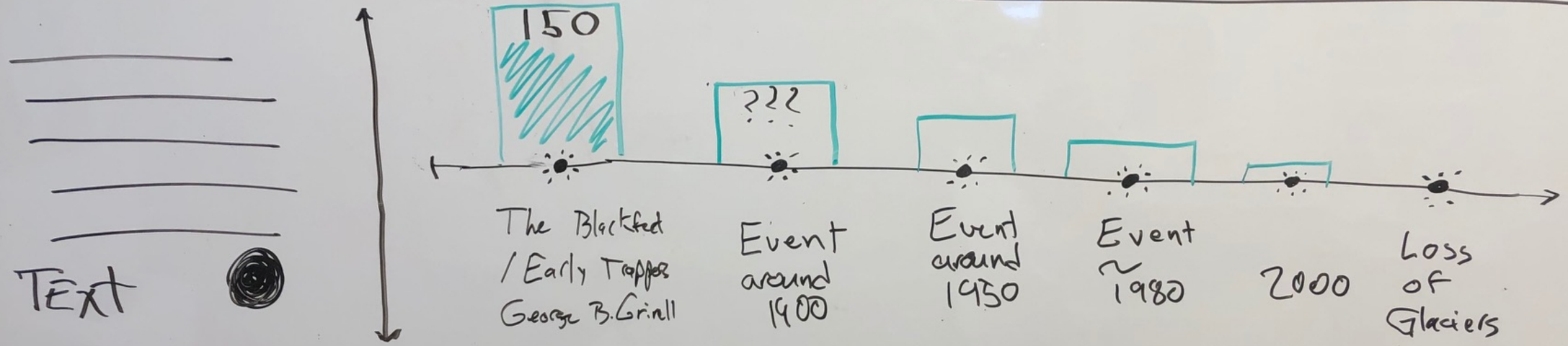
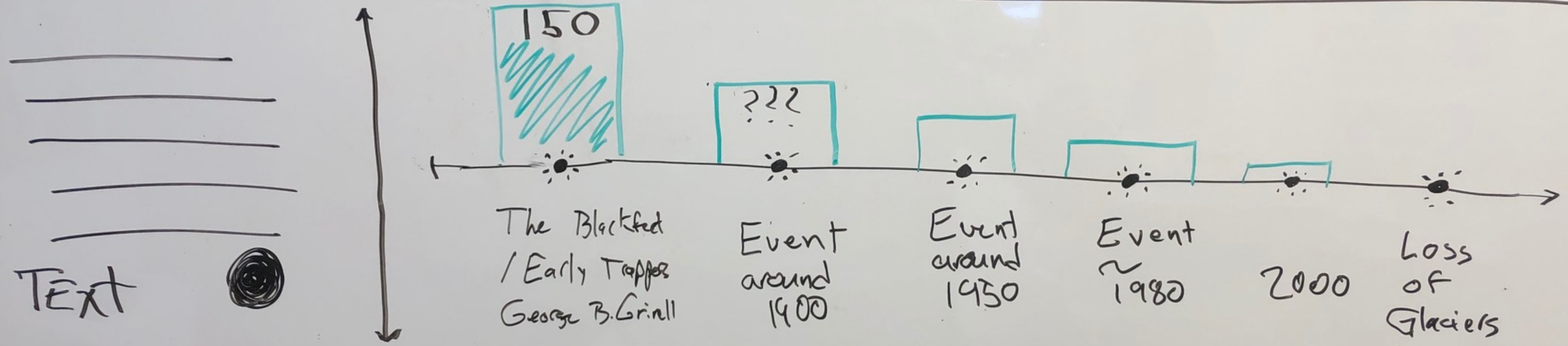
Goodbye to the Glaciers



Goodbye to the Glaciers



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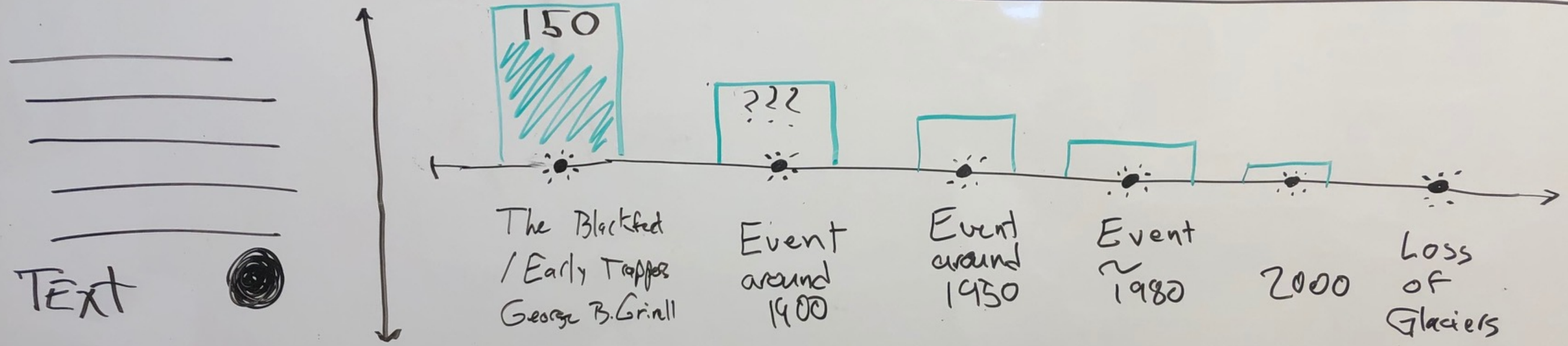

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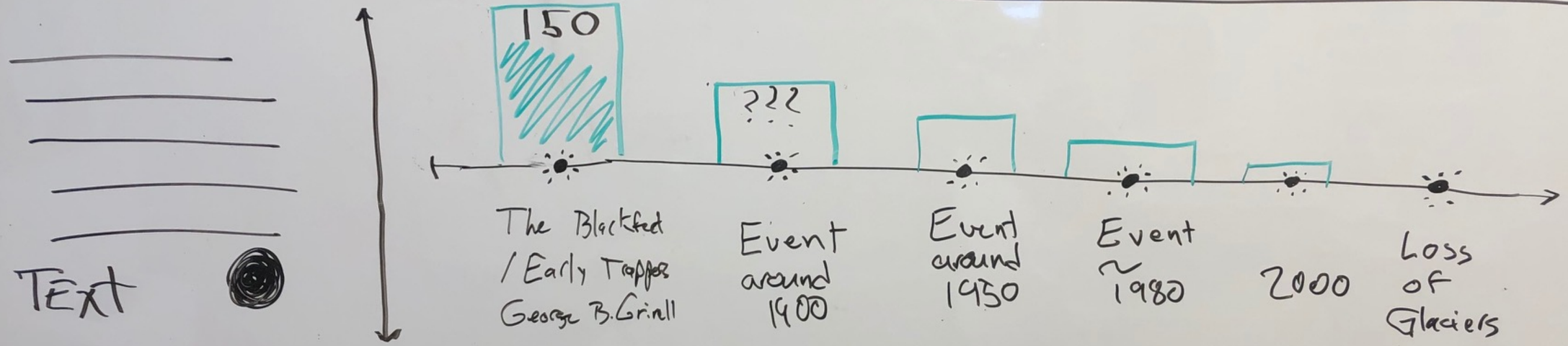

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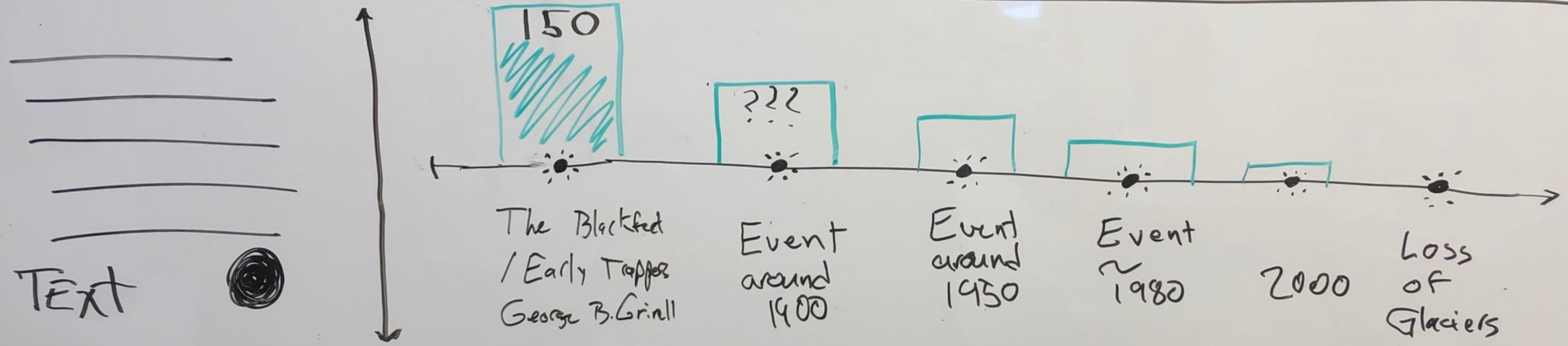

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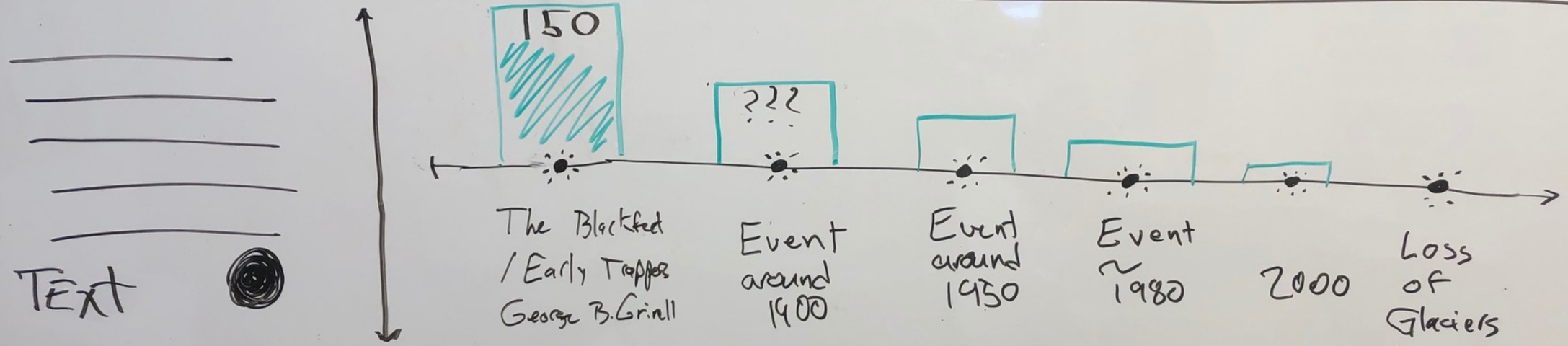

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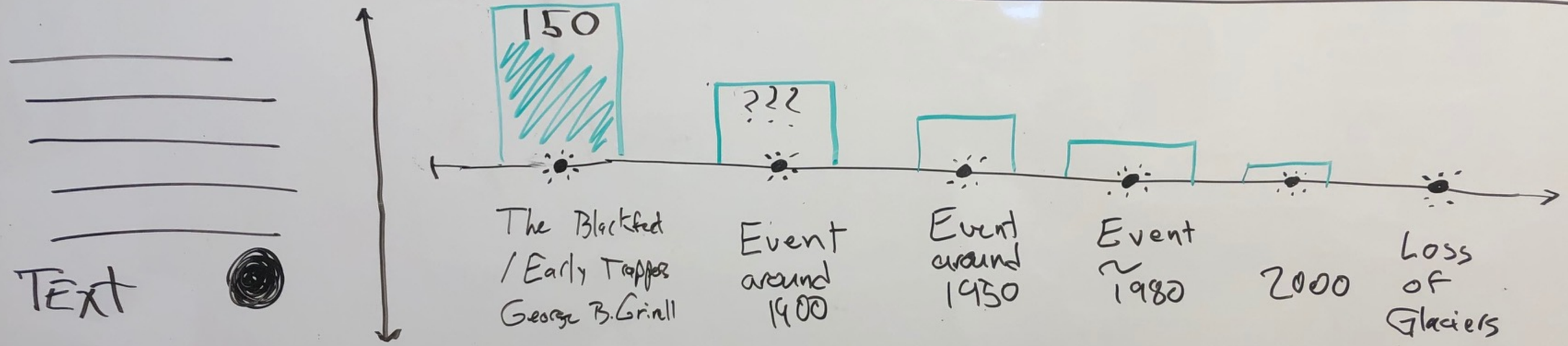

Conversation Contents

Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

"Florentine, Caitlyn" <cflorentine@usgs.gov>

From:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Sent:	Fri Feb 08 2019 13:42:18 GMT-0700 (MST)
To:	Daniel Lombardi <daniel_lombardi@nps.gov>
CC:	Daniel Fagre <dan_fagre@usgs.gov>, Lisa L Mckeon <lisa_mckeon@usgs.gov>
Subject:	Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

Hello Daniel,

Thank you for jump starting this important work! I am booked for the next few work days, but plan on contributing to this conversation next week.

Best regards,
Caitlyn

On Thu, Feb 7, 2019 at 5:14 PM Daniel Lombardi (via Google Docs) <drive-shares-noreply@google.com> wrote:

daniel_lombardi@nps.gov has invited you to **edit** the following document:

ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

It wasn't exactly easy but I found the original files for these exhibits that we've known needed fixed for awhile. It was a whole other ordeal to find the fonts!

Hopefully this group can help me update the text and come up with a plan to update the physical exhibits, which might not be easy considering the electronics.

The exhibits were originally made in 2009 by a company in Seattle called EDX.
http://www.edxseattle.com/portfolio/glacier-national-park-st-mary-visitor-center/

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Caitlyn Florentine, PhD
USGS Northern Rocky Mountain Science Center
215 Mather Drive
West Glacier, MT 59936
cflorentine@usgs.gov
406-888-7924 (office)
303-548-7693 (cell)

"Florentine, Caitlyn" <cflorentine@usgs.gov>

From:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Sent:	Wed Feb 13 2019 17:29:25 GMT-0700 (MST)
To:	Daniel Lombardi <daniel_lombardi@nps.gov>
CC:	Daniel Fagre <dan_fagre@usgs.gov>, Lisa L Mckeon <lisa_mckeon@usgs.gov>
Subject:	Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

Hi Daniel,

I concur with Lisa's comments in the shared document.

Please continue to reach out as the exhibit update proceeds, and thank you for giving us an opportunity to be involved.

Cheers,
Caitlyn

On Fri, Feb 8, 2019 at 1:42 PM Florentine, Caitlyn <cflorentine@usgs.gov> wrote:

> Hello Daniel,
>
> Thank you for jump starting this important work! I am booked for the next few work days, but plan on contributing to this conversation next week.
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> Best regards,
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"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Sun Feb 24 2019 10:58:02 GMT-0700 (MST)
To:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

Hi Daniel,

I wanted to make sure you knew that I did see your email on this. I figured that I'd wait until Lee was back this week, so we could both take a look at it together. Do you have a deadline for feedback?

Thanks,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

I am a *proud* graduate of the GOAL Leadership Academy. Ask me about the program!

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon Feb 25 2019 08:28:05 GMT-0700 (MST)
To:	"Smith, Deborah" <debby_smith@nps.gov>
Subject:	Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

Thanks, that sounds good.

No deadline but our current project calendar says we'd like to have the whole problem solved by the end of May. Since the design changes probably just include text edits I can do that very quickly. The harder part will be the fabrication.

A few questions we'll need your help answering...

- I don't remember with certainty what happens when, after pushing the button, the light gets to the 2020 spot. Do no more lights illuminate on the map?
- Can the panel be practically removed from the table map?
- Would it be bad if we couldn't exactly match the color on a reprint if we make it in the sign shop?
- Would it be better to have the company who first made the exhibit remake it?

Thanks for your help!

-daniel

On Sun, Feb 24, 2019 at 10:58 AM Smith, Deborah <debby_smith@nps.gov> wrote:

> Hi Daniel,
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> I wanted to make sure you knew that I did see your email on this. I figured that I'd wait until Lee was back this week, so we could both take a look at it together. Do you have a deadline for feedback?
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Daniel Lombardi
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406-888-7933

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Wed Feb 27 2019 09:24:00 GMT-0700 (MST)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

Hi Daniel,

I'll take to make a trip over to the VC this weekend/early next week, so I can verify the answers to your questions. I'd just like to double-check, so I'm not doing it from memory. Lee and I also talked about this briefly yesterday and we'll try to get back to you very soon related to the text. That would be great to get it all resolved before the VC opens for the season :-)

Thanks,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

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406-888-7933

"Smith, Deborah" <debby_smith@nps.gov>

From:	"Smith, Deborah" <debby_smith@nps.gov>
Sent:	Wed Feb 27 2019 09:28:36 GMT-0700 (MST)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

Oh, I hope it's okay. I added Lee to the editors for the file you shared.

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

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Sent:	Wed Feb 27 2019 09:32:41 GMT-0700 (MST)
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From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed Feb 27 2019 16:15:50 GMT-0700 (MST)
To:	"Smith, Deborah" <debby_smith@nps.gov>, Lee Rademaker

Subject: <lee_rademaker@nps.gov>
Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

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"Rademaker, Lee" <lee_rademaker@nps.gov>

From:	"Rademaker, Lee" <lee_rademaker@nps.gov>
Sent:	Wed Feb 27 2019 16:32:39 GMT-0700 (MST)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: ST MARY VISITOR CENTER EXHIBITS ON GLACIERS - Invitation to edit

Hey Daniel,

Thanks for sharing that. It is crazy how our own desire to be accurate came back to bite us when we didn't make it a priority to keep things up to date. I'm sure once we get the new sign completed and installed we will hear about this all over again after their 2019 expedition to Grinnell.

Best,
Lee

Lead Interpreter
Hudson Bay District
Glacier National Park
406-732-7791
Days off: Saturday / Sunday

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Sent:	Wed Feb 27 2019 16:33:10 GMT-0700 (MST)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>
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daniel_lombardi@nps.gov has invited you to **edit** the following document:

ST MARY VISITOR CENTER EXHIBITS ON GLACIERS

It wasn't exactly easy but I found the original files for these exhibits that we've known needed fixed for awhile. It was a whole other ordeal to find the fonts!

Hopefully this group can help me update the text and come up with a plan to update the physical exhibits, which might not be easy considering the electronics.

The exhibits were originally made in 2009 by a company in Seattle called EDX. http://www.edxseattle.com/portfolio/glacier-national-park-st-mary-visitor-center/

Open in Docs

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--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

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Conversation Contents

Glacier Graphics

Attachments:

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/24. Glacier Graphics/2.3 JacksonGlacier_66-15mockup.jpg
/24. Glacier Graphics/3.1 Jackson_GNP_091516_1033sm.jpg
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/24. Glacier Graphics/42.2 USGSglacier area summary_acres.pdf
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/24. Glacier Graphics/57.1 CHANGING WITH THE TIMES.png
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/24. Glacier Graphics/58.1 CHANGING WITH THE TIMES.png
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/24. Glacier Graphics/73.1 Rainy Birds-8332.jpg

/24. Glacier Graphics/73.2 Rainy Birds-8329.jpg

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed Jul 05 2017 09:58:37 GMT-0600 (MDT)
To:	Lisa Mckeon <lisa_mckeon@usgs.gov>
Subject:	Glacier Graphics

Hey Lisa,

I'm an exhibits specialist for the park and we're working on redoing the Jackson Glacier overlook wayside exhibit on the east side of GTTS Road.

I heard you might have some visual data and/or graphics that we might find useful. How should we go about getting those from you? We're still in the brainstorming stage and we'd be really open to any ideas you might have for us on this sign.

Thanks for your thoughts,

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"Mckeon, Lisa" <lisa_mckeon@usgs.gov>

From:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Sent:	Wed Jul 05 2017 14:20:50 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: Glacier Graphics
Attachments:	Jackson_GNP_091516_1033sm.jpg Jackson_GNP_091516_1009sm.jpg JacksonGlacier_66-15mockup.jpg

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406/888-7924 wk
406/888-7923 fax
lisa_mckeon@usgs.gov

https://www.usgs.gov/norock/ccme

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From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed Jul 05 2017 14:22:54 GMT-0600 (MDT)

To:	"Edgell, Erin" <erin_edgell@nps.gov>, "Feller, Quinn" <quinn_feller@nps.gov>
Subject:	Fwd: Glacier Graphics
Attachments:	Jackson_GNP_091516_1033sm.jpg Jackson_GNP_091516_1009sm.jpg JacksonGlacier_66-15mockup.jpg

---------- Forwarded message ----------
From: **Mckeon, Lisa** <lisa_mckeon@usgs.gov>
Date: Wed, Jul 5, 2017 at 2:20 PM
Subject: Re: Glacier Graphics
To: "Lombardi, Daniel" <daniel_lombardi@nps.gov>

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From:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Sent:	Wed Jul 05 2017 16:00:04 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: Glacier Graphics

Daniel,

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From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Wed Jul 05 2017 17:08:12 GMT-0600 (MDT)
To:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Subject:	Re: Glacier Graphics

Hey Lisa,

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"Mckeon, Lisa" <lisa_mckeon@usgs.gov>

From:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Sent:	Wed Jul 12 2017 08:53:26 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: Glacier Graphics

Daniel,

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent: Wed Aug 09 2017 12:08:35 GMT-0600 (MDT)

To: "Mckeon, Lisa" <lisa_mckeon@usgs.gov>, "Feller, Quinn" <quinn_feller@nps.gov>, "Edgell, Erin" <erin_edgell@nps.gov>

Subject: Re: Glacier Graphics

Hey Lisa,

We are starting to focus on this wayside exhibit a little more closely now. I've included Quinn and Erin, my coworkers also designing this wayside, in this email.

I've noticed the New York Times and your data sets include 39 glaciers. I thought there were 26 remaining glaciers in the park? Should we include the others that are no longer technically glaciers in our sign?

We are thinking about showing all 26 glaciers on the sign in the New York Times style with the Jackson Glacier larger in the middle. We've also thought about only doing the Jackson/Blackfoot Glaciers in NYTimes style and listing the others as pie graphs that show amount melted.

When you create the NYTimes style graphics do you just trace the satellite images in the 'Graphics to Accompany USGS Data Release' folder found here with Adobe Illustrator? If so, do some of them already exist as Illustrator files? Is there any thing else we should know about how you create those graphics?

Thanks for your help with this!

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"Edgell, Erin" <erin_edgell@nps.gov>

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Sent: Wed Aug 09 2017 12:18:33 GMT-0600 (MDT)
To: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject: Re: Glacier Graphics

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https://www.usgs.gov/norock/ccme

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Erin Edgell
Exhibits Specialist

Glacier National Park
West Glacier, MT 59936
406-888-7914

"Mckeon, Lisa" <lisa_mckeon@usgs.gov>

From:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Sent:	Wed Aug 09 2017 16:42:27 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	"Feller, Quinn" <quinn_feller@nps.gov>, "Edgell, Erin" <erin_edgell@nps.gov>
Subject:	Re: Glacier Graphics

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From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon Aug 14 2017 09:23:44 GMT-0600 (MDT)
To:	"Feller, Quinn" <quinn_feller@nps.gov>, "Edgell, Erin" <erin_edgell@nps.gov>
Subject:	Re: Glacier Graphics
Attachments:	IMG_5440.JPG

Here's the a glacier sign at the Grinnell Trailhead.

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Sent:	Mon Aug 14 2017 09:31:29 GMT-0600 (MDT)
To:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>, "Feller, Quinn" <quinn_feller@nps.gov>, "Edgell, Erin" <erin_edgell@nps.gov>, William Hayden <bill_hayden@nps.gov>
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CC:	"Edgell, Erin" <erin_edgell@nps.gov>, "Lombardi, Daniel" <daniel_lombardi@nps.gov>
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Quinn Feller

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon Aug 14 2017 11:43:02 GMT-0600 (MDT)
To:	"Mckeon, Lisa" <lisa_mckeon@usgs.gov>
Subject:	Re: Glacier Graphics

Okay, that'd be great, Lisa. We'd be happy to meet with Caitlyn.

On Mon, Aug 14, 2017 at 11:41 AM, Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

Shoot. I'm going to be gone all of next week on vacation, but one of my co-workers may be interested. We often talk of the importance of getting the science out there and good messaging so we appreciate being part of the process. I could ask Caitlyn Florentine, my co-worker who is very familiar with the glaciers and these layers.

Lisa

Lisa McKeon
USGS - Glacier Field Station
Glacier National Park
West Glacier MT 59936
406/888-7924 wk
406/888-7923 fax
lisa_mckeon@usgs.gov

https://www.usgs.gov/norock/ccme

On Mon, Aug 14, 2017 at 11:34 AM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Sorry, next week would bet better. We're not ready this week.

On Mon, Aug 14, 2017 at 11:31 AM, Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

Yes - I'd be happy to meet with you. I'll be at work this afternoon (1-5) and tomorrow from 8-12. What works for you?

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To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	"Feller, Quinn" <quinn_feller@nps.gov>, "Edgell, Erin" <erin_edgell@nps.gov>, William Hayden <bill_hayden@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>
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Subject:	Re: Glacier Graphics

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406/888-7923 fax
lisa_mckeon@usgs.gov

https://www.usgs.gov/norock/ccme

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"Florentine, Caitlyn" <cflorentine@usgs.gov>

From:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Sent:	Fri Aug 18 2017 08:20:07 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	"Feller, Quinn" <quinn_feller@nps.gov>, "Edgell, Erin" <erin_edgell@nps.gov>, William Hayden <bill_hayden@nps.gov>
Subject:	Re: Glacier Graphics

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Subject: Re: Glacier Graphics

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Subject:	Re: Glacier Graphics

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Sorry for the delayed response. I'd love to meet up real quickly this afternoon if that's OK.

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Subject: Re: Glacier Graphics

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Subject:	Re: Glacier Graphics
Attachments:	Sperry_gray1966_blue2015.eps Sperry_gray1966_blue2015.png

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Another thing, we're looking for new research related to the effects of climate change on avalanches and avalanche chutes. Do you know of someone at the USGS doing research into this subject?

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"Florentine, Caitlyn" <cflorentine@usgs.gov>

From:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
Sent:	Sat Aug 26 2017 15:47:07 GMT-0600 (MDT)
To:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
CC:	Lisa L Mckeon <lisa_mckeon@usgs.gov>
Subject:	Re: Glacier Graphics
Attachments:	Moon_Saying Goodbye to Glaciers.pdf Marzeion_Science_2014.pdf Roe_2016_NatureGeo.pdf Losing a Namesake_cf.pptx

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Attached are references from the scientific literature that I referenced as I wrote. If you have any questions, I am happy to answer them, and will be here in West Glacier both Thursday and Friday next week if you want to touch base in person. Otherwise I am passing the baton back to Lisa to be your point person for imagery, figures, and data access.

Thank you again for including us in this process. It is exciting and meaningful work.

I will send a separate email about the Triple Divide sign just to keep things clear.

Best regards,
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p.s. The attached Marzeion pub was referenced in the NYT article in the sentence "But scientists have attributed more recent melting to human-caused global warming."

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Awesome, thank you Caitlyn!

That .eps file, as you have prepared it, will work exactly as I hoped. I can open the .eps file in Illustrator and easily make color, size, texture, and orientation adjustments as needed. Then I can easily drop those into the wayside exhibit.

That leads to another question that we did not discuss. That is, how should we, or should we, preserve the relative scale between the glaciers?

I've attached a PDF of the Triple Divide Peak Wayside for your further comment. Feel free to share with other people that you think might be helpful but obviously don't share it publicly. I have also attached a PNG because the rivers in the PDF might look terrible depending on how they're viewed.

Thanks again,

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Hi Daniel,

It was such a pleasure meeting with you this afternoon. Attached are a few mock files of Sperry Glacier change (1966 and 2015) you can fiddle around with. Let me know which file format best serves your design needs. I look forward to ongoing collaboration.

Cheers,
Caitlyn

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Okay, that sounds really great!

See you at 4PM!

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Hi Daniel,

Sure, later in the afternoon works for me. Want to swing by our office around 4pm? I am on the first floor in the building labeled USGS Global Change (215

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Sent:	Mon Aug 28 2017 08:49:21 GMT-0600 (MDT)
To:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
CC:	Lisa L Mckeon <lisa_mckeon@usgs.gov>
Subject:	Re: Glacier Graphics

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Thanks for your thoughts,

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon Aug 28 2017 08:49:42 GMT-0600 (MDT)
To:	William Hayden <bill_hayden@nps.gov>, "Feller, Quinn" <quinn_feller@nps.gov>, "Edgell, Erin" <erin_edgell@nps.gov>
Subject:	Fwd: Glacier Graphics
Attachments:	Moon_Saying Goodbye to Glaciers.pdf Marzeion_Science_2014.pdf Roe_2016_NatureGeo.pdf Losing a Namesake_cf.pptx

---------- Forwarded message ----------
From: **Florentine, Caitlyn** <cflorentine@usgs.gov>
Date: Sat, Aug 26, 2017 at 3:47 PM
Subject: Re: Glacier Graphics
To: "Lombardi, Daniel" <daniel_lombardi@nps.gov>

Cc: Lisa L Mckeon <lisa_mckeon@usgs.gov>

Hi Daniel,

Happy to hear that the .eps file works well. I am copying Lisa here so that she is looped back into our exchange. She will likely be more responsive and available in the coming weeks, as my research and teaching commitments ramp up with the start of the school year. So I wanted to make sure she is caught up.

- I strongly recommend maintaining scale and orientation, so that viewers can see the relative size and aspect (cardinal orientation) of the glaciers at a glance.

- With that in mind I went ahead and created .eps files that include a scale bar and north arrow for all of the 37 named glaciers within the Park (see Drive folder "Glaciers_eps"). With the scale bar you should be able to import vector files to the wayside and adjust their size without losing relative scale. You can line up the 1 km scale bars to match, then clip them out once you have everything arranged the way you want it. This might be a sub-optimal way of doing it, but it should work. Note that Grinnell, Salamander, and Gem Glaciers are all within one file, as are Blackfoot and Pumpelly. Some of the files include corners of other glaciers (e.g. Jackson). I am assuming you can clip and crop to separate features within the same image.

Note for Lisa: *Daniel and his team are working outside the geographic domain, i.e. not in ArcGIS, so it seemed easiest for us to leverage our existing ArcGIS skills and software rather than have them spin up from scratch. If this gets arduous we can figure out a better way to work, but for the sake of expediency I figured this approach was okay.*

- I was bold enough to attach a revised draft that includes Lisa's idea for visualizing glacier volume change. I don't know if it works, and it obviously needs beautifying, but I liked her idea of using repeat photos to show glacier thinning, to get at the third dimension of glacier change. This way, all the glacier area change figures will be to one scale (getting rid of the blown-up Jackson fig at the top, which was cool for showing orientation, but might be confusing if all the others are in the same orientation and scale). This revised draft still features Jackson Glacier (now with the photo) to connect the sign's narrative to the site. What do you think?

- I took a shot at improving the blurb language, too. Please take this with a grain of salt. You are by no means bound to using it. It is helpful for me to sit down and think about how these ideas are communicated, so my effort here will not be wasted even if you and your team decide to go a different direction. I tried to make the text match your nice 3 communication bullet points:

1) Area is not volume (now addressed in the photo caption and annotations)
2) All glaciers in GNP have retreated, but not in the same way
3) Glaciers are retreating because of climate change

Attached are references from the scientific literature that I referenced as I wrote. If you have any questions, I am happy to answer them, and will be here in West Glacier both Thursday and Friday next week if you want to touch base in person. Otherwise I am passing the baton back to Lisa to be your point person for imagery, figures, and data

access.

Thank you again for including us in this process. It is exciting and meaningful work.

I will send a separate email about the Triple Divide sign just to keep things clear.

Best regards,
Caitlyn

p.s. The attached Marzeion pub was referenced in the NYT article in the sentence "But scientists have attributed more recent melting to human-caused global warming."

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"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Mon Aug 28 2017 16:03:19 GMT-0600 (MDT)
To:	"Florentine, Caitlyn" <cflorentine@usgs.gov>
CC:	Lisa L Mckeon <lisa_mckeon@usgs.gov>
Subject:	Re: Glacier Graphics

Hey Caitlyn and Lisa,

I met with the team today and we had a full discussion on how to proceed with this and things are looking good.

One thing we'd like to do is try and use some repeat photographs. Can you help me access the full resolution repeat photos of Jackson Glacier? Additionally, if there's a historic photograph of Jackson Glacier taken from that spot on the GTTS Road that would be extra helpful. Do you know if such a photo exists? We might have to look in the park archives.

Another thing we wanted to get clear: In 1966 there were 37 active glaciers in the park?

Thanks for your help,

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On Mon, Aug 28, 2017 at 8:49 AM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Awesome, thank you Caitlyn and Lisa,

This will work quite well. We can use all these .EPS files to create our sign - I doubt we'll need much more help from you with ArcGIS.

I will show all this to my colleagues and we'll start getting to work.

Thanks again,

-daniel

On Sat, Aug 26, 2017 at 3:47 PM, Florentine, Caitlyn <cflorentine@usgs.gov> wrote:

Hi Daniel,

Happy to hear that the .eps file works well. I am copying Lisa here so that she is looped back into our exchange. She will likely be more responsive and available in the coming weeks, as my research and teaching commitments ramp up with the start of the school year. So I wanted to make sure she is caught up.

- I strongly recommend maintaining scale and orientation, so that viewers can see the relative size and aspect (cardinal orientation) of the glaciers at a glance.

- With that in mind I went ahead and created .eps files that include a scale bar and north arrow for all of the 37 named glaciers within the Park (see Drive folder "Glaciers_eps"). With the scale bar you should be able to import vector files to the wayside and adjust their size without losing relative scale. You can line up the 1 km scale bars to match, then clip them out once you have everything arranged the way you want it. This might be a sub-optimal way of doing it, but it should work. Note that Grinnell, Salamander, and Gem Glaciers are all within one file, as are Blackfoot and Pumpelly. Some of the files include corners of other glaciers (e.g. Jackson). I am assuming you can clip and crop to separate features within the same image.

Note for Lisa: *Daniel and his team are working outside the geographic domain, i.e. not in ArcGIS, so it seemed easiest for us to leverage our existing ArcGIS skills and software rather than have them spin up from scratch. If this gets arduous we can figure out a better way to work, but for the sake of expediency I figured this approach was okay.*

- I was bold enough to attach a revised draft that includes Lisa's idea for visualizing glacier volume change. I don't know if it works, and it obviously needs beautifying, but I liked her idea of using repeat photos to show glacier thinning, to get at the third dimension of glacier change. This way, all the glacier area change figures will be to one scale (getting rid of the blown-up Jackson fig at the top, which was cool for showing orientation, but might be confusing if all the others are in the same

orientation and scale). This revised draft still features Jackson Glacier (now with the photo) to connect the sign's narrative to the site. What do you think?

- I took a shot at improving the blurb language, too. Please take this with a grain of salt. You are by no means bound to using it. It is helpful for me to sit down and think about how these ideas are communicated, so my effort here will not be wasted even if you and your team decide to go a different direction. I tried to make the text match your nice 3 communication bullet points:

1) Area is not volume (now addressed in the photo caption and annotations)
2) All glaciers in GNP have retreated, but not in the same way
3) Glaciers are retreating because of climate change

Attached are references from the scientific literature that I referenced as I wrote. If you have any questions, I am happy to answer them, and will be here in West Glacier both Thursday and Friday next week if you want to touch base in person. Otherwise I am passing the baton back to Lisa to be your point person for imagery, figures, and data access.

Thank you again for including us in this process. It is exciting and meaningful work.

I will send a separate email about the Triple Divide sign just to keep things clear.

Best regards,
Caitlyn

p.s. The attached Marzeion pub was referenced in the NYT article in the sentence "But scientists have attributed more recent melting to human-caused global warming."

On Thu, Aug 24, 2017 at 5:43 PM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

> Awesome, thank you Caitlyn!
>
> That .eps file, as you have prepared it, will work exactly as I hoped. I can open the .eps file in Illustrator and easily make color, size, texture, and orientation adjustments as needed. Then I can easily drop those into the wayside exhibit.
>
> That leads to another question that we did not discuss. That is, how should we, or should we, preserve the relative scale between the glaciers?
>
> I've attached a PDF of the Triple Divide Peak Wayside for your further comment. Feel free to share with other people that you think might be helpful but obviously don't share it publicly. I have also attached a PNG because the rivers in the PDF might look terrible depending on how they're viewed.
>
> Thanks again,
>
> -daniel
>
> On Thu, Aug 24, 2017 at 5:27 PM, Florentine, Caitlyn <cflorentine@usgs.gov>

wrote:

Hi Daniel,

It was such a pleasure meeting with you this afternoon. Attached are a few mock files of Sperry Glacier change (1966 and 2015) you can fiddle around with. Let me know which file format best serves your design needs. I look forward to ongoing collaboration.

Cheers,
Caitlyn

On Thu, Aug 24, 2017 at 8:31 AM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Okay, that sounds really great!

See you at 4PM!

On Thu, Aug 24, 2017 at 8:29 AM, Florentine, Caitlyn <cflorentine@usgs.gov> wrote:

Hi Daniel,

Sure, later in the afternoon works for me. Want to swing by our office around 4pm? I am on the first floor in the building labeled USGS Global Change (215 Mather Drive). Lisa is the expert on generating digital outlines of the glaciers, but I can tell you what I know. I also am excited to share other insight from our glacier research. See you this afternoon.

Cheers,
Caitlyn

On Thu, Aug 24, 2017 at 7:32 AM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

I'm available anytime in the afternoon. Maybe toward the end of the day would work well?

On Thu, Aug 24, 2017 at 7:31 AM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Hey Caitlyn,

Sorry for the delayed response. I'd love to meet up real quickly this afternoon if that's OK.

Maybe I should actually come by your office? I'd really like to see how you make the GIS satellite outlines of the glaciers. Would you be able to show me that?

Thanks so much!

-daniel

On Wed, Aug 23, 2017 at 3:02 PM, Florentine, Caitlyn

<cflorentine@usgs.gov> wrote:

Hi Daniel,

Are you and your team still interested in chatting about your sign sometime tomorrow or Friday? I am available whenever. Looking forward to it.

Cheers,
Caitlyn

On Fri, Aug 18, 2017 at 8:20 AM, Florentine, Caitlyn <cflorentine@usgs.gov> wrote:

Hi Daniel,
Sorry for my slow reply. Yes, next Thursday (8/24) afternoon works for me. Looking forward to meeting and working with you and your team. Let me know what time specifically I should head over to HQ and I will see you then.
Cheers,
Caitlyn

On Tue, Aug 15, 2017 at 2:10 PM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Hey Caitlyn,

We're still working through things here on this sign. We hope to be ready to meet next Thursday afternoon if that works for you?

-daniel

On Tue, Aug 15, 2017 at 11:51 AM, Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

Daniel,

I'm out of the office all of next week, but Caitlyn Florentine is happy to meet with you next week about the wayside exhibit. She's cc'edin this email so you can arrange a time with her. We're excited to be involved.
Thanks,

Lisa

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lisa_mckeon@usgs.gov

https://www.usgs.gov/norock/ccme

On Mon, Aug 14, 2017 at 9:31 AM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Hey Lisa,

Do you think you'd have time to meet with us and to look at a draft next week and give us your thoughts?

-daniel

On Wed, Aug 9, 2017 at 4:42 PM, Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

Daniel,

Just to be clear, there are 37 NAMED glaciers in the park (plus 2 on adjacent FS land - Grant and Stanton Glaciers). Twenty-six of the named glaciers in GNP met the size criteria to be considered active glaciers as of our last published analysis.

I created the graphics in ArcGIS by displaying the 1966 and 2015 glacier margin layers. The layers are available here if you use ArcGIS. If you don't have access to GIS, I could probably get those to you with some specifications - what size and resolution, file type, etc. for your use?

I guess the messaging on your sign would determine whether or not to display all the named glaciers, or just the active glaciers. A map like this make an impact by distinguishing loss without even seeing the data.

One other point to make when using the area data is that it does not reflect the volume loss, which for many glaciers, is probably quite significant in terms of change between the same years, but those data are not available. This page may help you with that messaging if you want to go in to that. Some of the repeat photo pairs help visitors visualize the magnitude of volume loss. I could help you find an appropriate one if you like.

I'll be at Grinnell Glacier tomorrow, but would be happy to chat with you about any of this on Friday. I'll be working from home on Friday so if you need to call use (b) (6) [redacted].

Lisa

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On Wed, Aug 9, 2017 at 12:08 PM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Hey Lisa,

We are starting to focus on this wayside exhibit a little more closely now. I've included Quinn and Erin, my coworkers also designing this wayside, in this email.

I've noticed the New York Times and your data sets include 39 glaciers. I thought there were 26 remaining glaciers in the park? Should we include the others that are no longer technically glaciers in our sign?

We are thinking about showing all 26 glaciers on the sign in the New York Times style with the Jackson Glacier larger in the middle. We've also thought about only doing the Jackson/Blackfoot Glaciers in NYTimes style and listing the others as pie graphs that show amount melted.

When you create the NYTimes style graphics do you just trace the satellite images in the 'Graphics to Accompany USGS Data Release' folder found here with Adobe Illustrator? If so, do some of them already exist as Illustrator files? Is there any thing else we should know about how you create those graphics?

Thanks for your help with this!

-daniel

On Wed, Jul 12, 2017 at 8:53 AM, Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

Daniel,

Yes, we'd love to see what you've created and offer feedback. Send along a draft when you are ready.

Lisa

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On Wed, Jul 5, 2017 at 5:08 PM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Hey Lisa,

After talking with my team more today I don't know that we need anything more at this point.

We want to see what we can come up with using the data/images you've provided in the next couple weeks. After we make a little progress would you be interested in meeting with us and giving feedback?

-daniel

On Wed, Jul 5, 2017 at 4:00 PM, Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

Daniel,

I'll be able to help you with the satellite images on Wed. and Thur. of next week, when I'm back in the office. If I know just what you want it will go faster. I wasn't sure where you wanted the image cropped, what (if any) scale bar and N arrow to use...etc. Sketch what you'd like and I'll see if I can create it in Arc. Or do you just want the orthorectified tif file to do it yourself? I'll add one to the GoogleDrive folder that you can experiment with.

Lisa

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https://www.usgs.gov/norock/ccme

On Wed, Jul 5, 2017 at 2:20 PM, Mckeon, Lisa <lisa_mckeon@usgs.gov> wrote:

Daniel,

I just shared a GoogleDrive folder that has some graphics of Jackson Glacier (and others) and data table that details the change in area between 1966- 2015 which you might want to pull from. We've contracted flights for research purposes and have some nice aerial images of Jackson which you could use (a couple samples attached), as well as these Jackson Glacier repeat photos (click on each image for download options). I have higher resolution photos available of all of these if you decide you want to use any.

We've been mapping the margins of the glaciers and just completed mapping the 1850 glacier extent based on evidence of moraines. I don't have the 1850 layer at my access, but we may be able to provide it for some sort of graphic like the GoogleEarth screenshot that's attached (grey = 1966, gold = 2015). I think it's kind of a neat effect, and pretty easy for most people to interpret, to overlay the margins within this GoogleEarth-type visual. The 1850 margin goes way down to the trees and shows a large contrast in size from current (2015) margin. Let me know if you'd be interested in shapefiles to create something.

Those are a few ideas, but I'm not sure what the overall message you're trying to

convey is. Being as Jackson is one of the few glaciers visible from the roadside I assumed that it would be something about glacier recession. I'm happy to talk or provide anything else - just let me know. Thanks for asking!

Lisa

Lisa

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https://www.usgs.gov/norock/ccme

On Wed, Jul 5, 2017 at 9:58 AM, Lombardi, Daniel <daniel_lombardi@nps.gov> wrote:

Hey Lisa,

I'm an exhibits specialist for the park and we're working on redoing the Jackson Glacier overlook wayside exhibit on the east side of GTTS Road.

I heard you might have some visual data and/or graphics that we might find useful. How should we go about getting those from you? We're still in the brainstorming stage and we'd be really open to any ideas you might have for us on this sign.

Thanks for your thoughts,

-daniel

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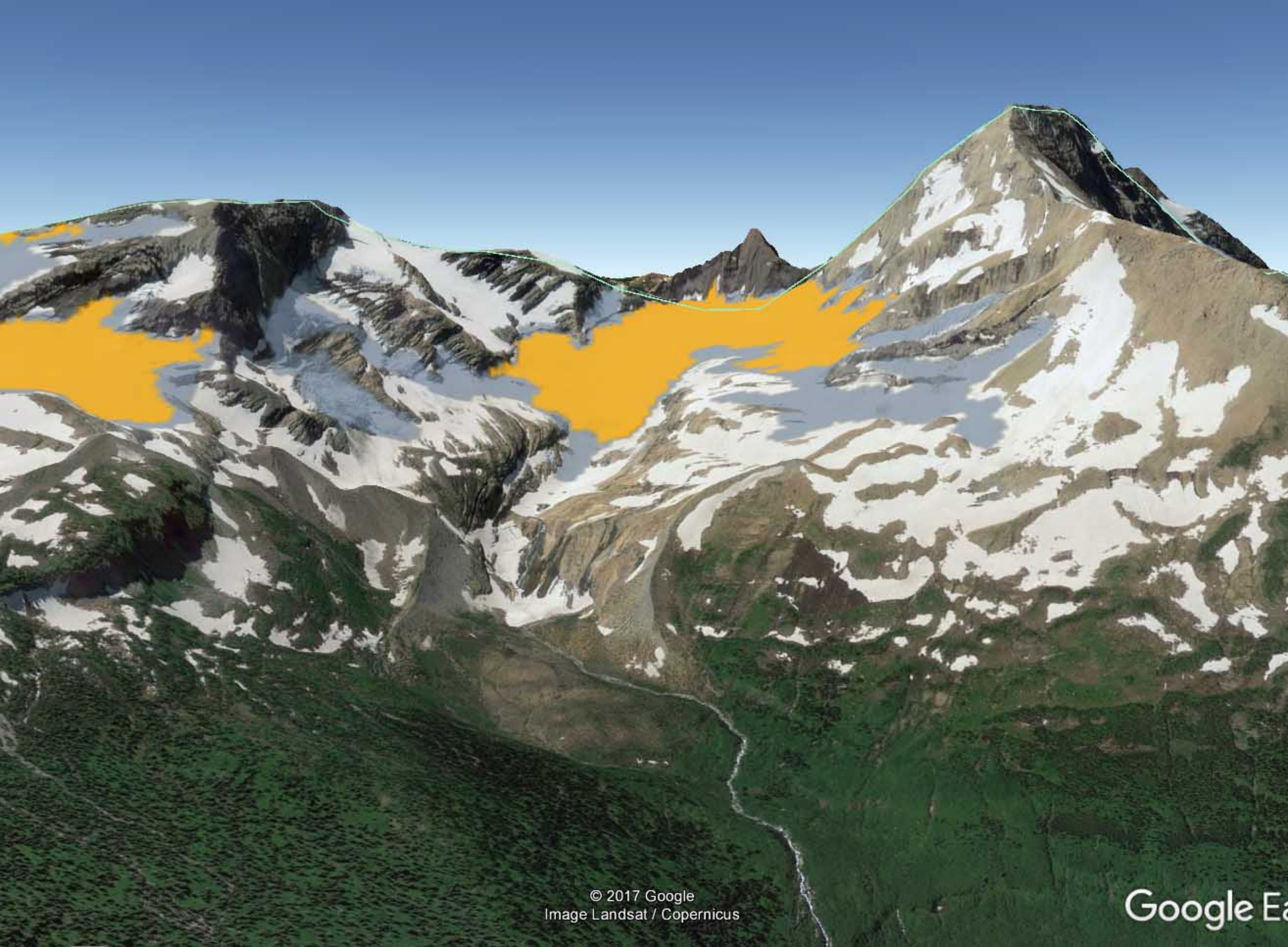
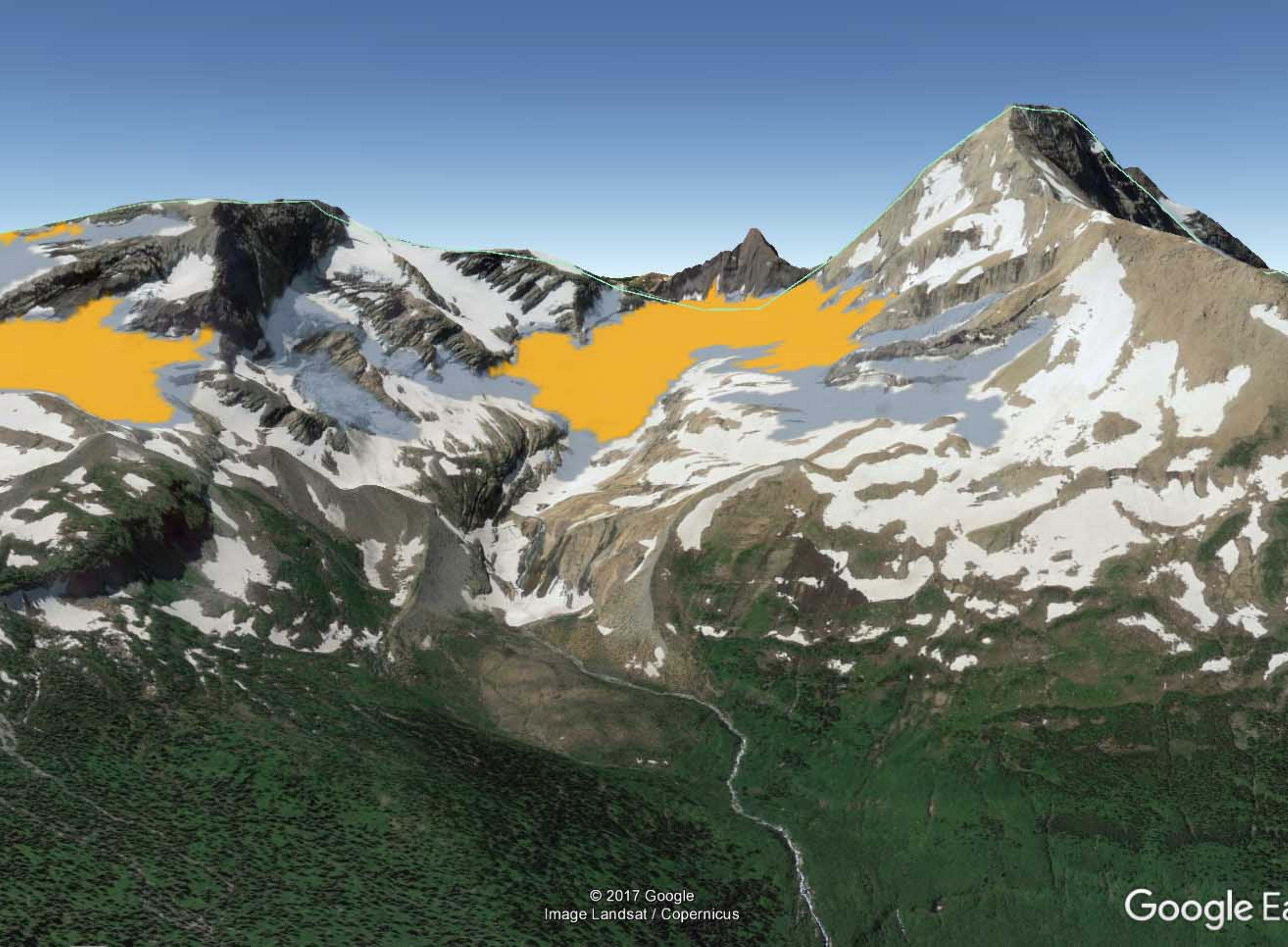
303-548-7693 (cell)

Lisa Mckeon <lisa_mckeon@usgs.gov>

From:	Lisa Mckeon <lisa_mckeon@usgs.gov>
Sent:	Tue Aug 29 2017 07:19:03 GMT-0600 (MDT)
To:	"Florentine, Caitlyn" <cflorentine@usgs.gov>, "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Subject:	Re: Glacier Graphics


© 2017 Google
Image Landsat / Copernicus
Google Ea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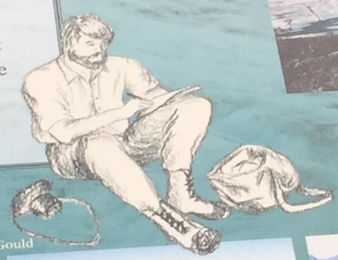
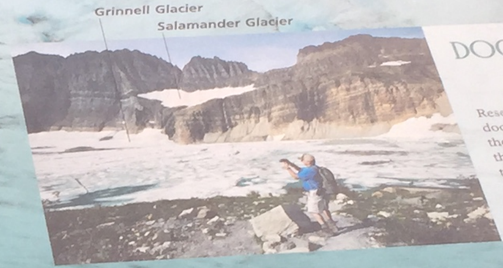
Glacier National Park

National Park Service
U.S. Department of the Interior

WITNESS THE CHANGE

Since the end of the Little Ice Age in the 1800s, Glacier's glaciers have been melting at an accelerated rate due to a warming trend, partially as a result of human activity. Researchers monitor glaciers like Grinnell through repeat photography. The park uses this information to determine plausible and possible future scenarios, and to protect park resources when the glaciers are gone.





DOCUMENT THE CHANGE

Researchers and visitors have been documenting Grinnell Glacier since the arrival of George Bird Grinnell in the late 1800s. The photo at left was taken in 2014. Take a photo from this common viewpoint and compare. What has changed?

1887

George Bird Grinnell's travel diary:

The glacier lies in a basin two miles wide by one and one-half deep and consists of two principal masses, one below, which covers far more ground than the one above, and another on a ledge above the first which is very thick and is constantly falling over onto the mass below.

Views of Grinnell Glacier from summit of Mt. Gould

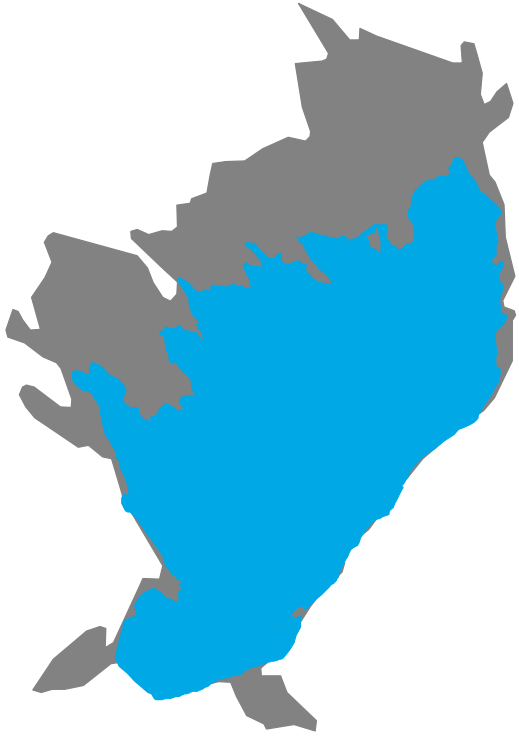
TJ HILEMAN

USGS/CARL KEY

USGS/DAN FAGRE

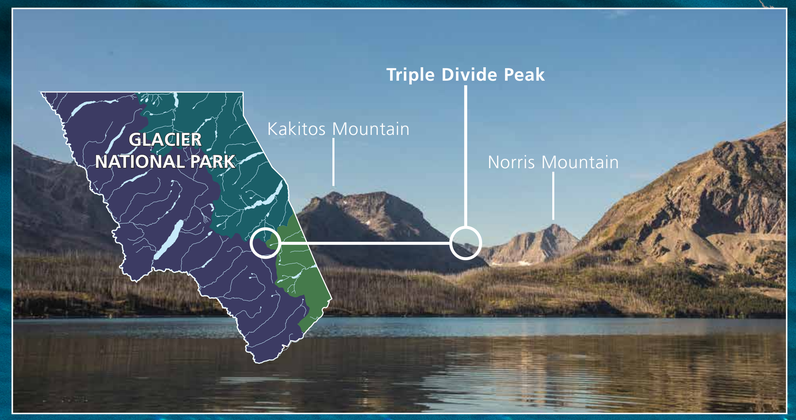
USGS/LINDSEY RENGSTON

USGS/KEVIN JACKS



National Park Service
U.S. Department of the Interior

It's All Downstream From Here



Triple Divide Peak, the distant mountain peeking out across the lake, is one of the few places in the world where three major watersheds descend from the same place. Glacier National Park's waters flow across the continent to very different places: the Pacific Ocean, Hudson Bay, and the Gulf of Mexico.

Glacial ice provides a critical source of water that sustains the habitats of countless plants and animals here and downstream. Protecting these pristine waters also supports agriculture, recreation, and industry across the continent. As the climate warms and glaciers melt, the store of water that nourishes the continent will dwindle. Though Triple Divide Peak seems far away, what happens here has effects that reach close to home.

YOU ARE HERE

West Glacier — Apgar Village — Lake McDonald Lodge — Avalanche Creek — The Loop — Logan Pass — Jackson Glacier Overlook — Rising Sun — St. Mary

ELEVATION		
Logan Pass	6646 ft	2026 m
Current Location	4512 ft	1372 m
West Glacier	3225 ft	983 m

DIRECTION

S E W N 160°

DISTANCE		
West Glacier	45.7 mi	73.5 km
Logan Pass	13.7 mi	22.0 km
St. Mary	3.9 mi	6.9 km

It's All Downstream From Here

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Glacial ice provides a critical source of water that sustains the habitats of countless plants and animals here and downstream. Protecting these pristine waters also supports agriculture, recreation, and industry across the continent. As the climate warms and glaciers melt, the store of water that nourishes the continent will dwindle. Though Triple Divide Peak seems far away, what happens here has effects that reach close to home.

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PHOTO: DANITA DELIMONT/GETTY IMAGES

CLIMATE CHANGE

Saying goodbye to glaciers

Glacier volume is shrinking worldwide, with wide-ranging implications for society

By **Twila Moon**

Global glacier volume is shrinking. This loss of Earth's land ice is of international concern. Rising seas, to which melting ice is a key contributor, are expected to displace millions of people within the lifetime of many of today's children. But the problems of glacier loss do not stop at sea level rise; glaciers are also crucial water sources, integral parts of Earth's air and water circulation systems, nutrient and shelter suppliers for flora and fauna, and unique landscapes for contemplation or exploration.

Finding that ice sheets can respond to climate change on subannual to decadal time scales, glaciology research surged in the early 21st century. Scientists now study the world's glaciers at many scales, from centimeter-scale in situ measurements to worldwide satellite-based monitoring campaigns.

Field studies facilitate detailed spatiotemporal sampling and deployment of coincident measurement suites, such as Global Positioning System (GPS), weather stations, seismometers, time-lapse cameras, and radar instruments. The results elucidate glacier hydrology, subsurface environments, and glacier dynamics on time scales of minutes to months. Aerial surveys cover inaccessible regions such as crevassed zones and even help with data acquisition between satellite missions.

To cover regions as large as ice sheets, space-borne satellite data are indispensable. Gravity-measuring satellites help estimate ice volume variations, altimetry satellites detect changing surface elevations, and optical and radar imaging satellites measure ice motion, monitor glacier advance and retreat, and observe surface properties, including melt. Growing in situ and satellite archives, along with glacier and ice sheet reconstruction efforts, are beginning to provide the longer records needed to separate glacier "climate" from glacier "weather" (*1*). The results from this surge in data and scientific effort point clearly to rapid and largely irreversible ice loss.

DISAPPEARING BEFORE OUR EYES

One of the most visible worldwide trends is glacier retreat. Photographs and aerial and satellite images of glaciers show consistent, substantial, and anomalous retreat from the Antarctic Peninsula through Patagonia, Kilimanjaro, and the Himalayas to Greenland and the Arctic. Iconic glaciers—such as many in Glacier National Park, Montana—have already disappeared. Modeling efforts suggest that this is only the beginning; studies project that 52% of all small glaciers in Switzerland will disappear in the next 25 years (*2*), western Canada will lose 70 ± 10% of its total glacier volume by 2100 (*3*), and glacier mass losses in coming decades will be substantial for most parts of the Himalaya (*4*). Some glaciers are bucking the retreat trend, but these responses are com-

National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, 449 UCB, University of Colorado, Boulder, CO 80309, USA. Email: twila.science@gmail.com

Downloaded from http://science.sciencemag.org/ on May 11, 2017

Published by AAAS

A melting iceberg calved from Jakobshavn Glacier floats at the mouth of Disko Bay, Ilulissat, Greenland.

monly due to cyclical glacier-sediment interactions that are independent of climate (*5*) or are consistent with environmental changes resulting from climate change, such as increased precipitation (*6*).

Measurements of total glacier ice mass change are no less disturbing. Synthesizing results from several distinct methods for measuring ice mass provides conclusive evidence that the Greenland and West Antarctic Ice Sheets are shrinking at accelerating rates (*7*). The step change in Greenland ice loss likely began in the early 1990s (*8*); along the Antarctic Peninsula, signs of destabilization have marched south over the past one to two decades (*9*). Some of the most sobering observations, though, come from the Thwaites and Pine Island Glaciers region of West Antarctica.

Containing ~5 m of potential sea level rise, the West Antarctic Ice Sheet is particularly vulnerable because it rests on bedrock well below sea level and is exposed to warm ocean waters at depth. This setting is the key ingredient for triggering an amplifying loop of ice loss called the marine ice sheet instability, in which retreat, thinning, and speedup at the ice sheet edge produce runaway ice loss. Multiple studies indicate that this irreversible West Antarctic collapse is under way (*10*, *11*). The safety band of ice that protects more rapid ice loss around other parts of the Antarctic coast, especially in West Antarctica, is also showing signs of weakening (*12*).

SCIENTIFIC CHALLENGES

The risks and impacts of a 1- or 2-m sea level rise differ substantially for coastal cities and island nations. But perhaps even more important for planning is whether that flooding occurs in 2050 or 2150. This question can only be addressed by constraining the rates of ice loss, which must be a top research priority. Determining ice loss rates requires continued development of monitoring capacity, a sustained focus on process studies, and further integration of observations and modeling efforts.

Recognition of the value of glacier and ice sheet monitoring has increased in the past decade, but challenges remain. Limited satellite imaging has been a roadblock in assessing multidecadal ice-sheet–wide change. Much of what we know today came from glaciologists thoughtfully pulling data from satellites for which ice sheet monitoring was not a primary mission directive. The result has been data that are not consistently sampled across space or time, supporting important insights but falling short of providing a complete picture of global changes. Thankfully, ice research is becoming a greater priority. For example, the planned NASA–Indian Space Research Organisation (ISRO) Synthetic Aperture Radar (SAR) mission (NISAR) satellite will be the first radar satellite for which monitoring Earth's ice sheets is a primary mission directive. Securing funding support for long-term on-the-ground monitoring efforts, however, remains difficult.

Process studies, which are often more easily accommodated by commonly 3-year grant cycles, continue to be key to understanding the mechanisms that control glacier behavior. Efforts to determine the role of hydrology in ice motion (*13*) and understand glacier and ice-sheet surface-darkening (*14*) are examples of important and necessary research paths. Integration of observations and models is also crucial; an example is the increasing partnership between the Ice Sheet Model Intercomparison (currently ISMIP6) and Greenland Ice Sheet–Ocean Interactions (GRISO) projects. Better connections across observation and modeling research can improve model parameterizations, increase confidence in future forecasts, and pinpoint areas where additional in situ and remote sensing studies are needed.

Combining tools should also help with another challenge: determining methods and best practices to merge studies with disparate spatial and temporal scales. The next frontier in glaciology includes better integrating scales important for critical glacier processes (tens to hundreds of meters) with efforts to understand and predict ice-sheet–wide changes (hundreds to thousands of kilometers). Progress on this front will require substantial cross-disciplinary collaboration.

BEYOND SEA LEVEL RISE

Given the wide-ranging effects of glacier ice loss, it is imperative that glaciologists increase efforts to reach across disciplines, applying a systems science approach to elucidate how ice loss is both affected by and affects other elements of the hydrosphere, biosphere, anthroposphere, and beyond. Although sea level rise is the most common alarm bell from the glaciology community, the impacts of losing ice encompass much more, from reducing water security (*4*) to altering ecosystems (*15*). Glaciologists need to capture this breadth in research, data dissemination, and outreach efforts. Indeed, disseminating findings beyond the science community is an activity that must be encouraged, supported, and recognized by universities, research institutions, and funding agencies.

The evidence is overwhelming: Earth is losing its ice. Much of this loss is irreversible and the result of human-caused climate change (*1*). Unless substantial climate response action is taken and the trend of global temperature rise is reversed, we will continue to see Miami streets swallowed by the sea and glacier freshwater reservoirs melt into mud. And we can expect this pattern to continue for decades, centuries, and indeed, millennia. As scientists, we must make this reality clear and help to ensure that action is taken to minimize impacts globally. ■

REFERENCES AND NOTES

1. G. H. Roe, M. B. Baker, F. Herla, *Nat. Geosci.* **10**, 95 (2016).
2. M. Huss, M. Fischer, *Front. Earth Sci.* **4**, 248 (2016).
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Saying goodbye to glaciers
Twila Moon (May 11, 2017)
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Editor's Summary

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and 10^{-1} s on the (100) facet. Therefore, the ability of the surfactant ligands to move on the surface allows the (111) facet to grow, whereas the low mobility of the ligands on the (100) facet blocks its growth. However, this mechanism is only for large facets. For small nanocrystals, the ligand molecules can easily fan out to make room for platinum atoms to land (*14*). Therefore, all facets grow when the nanocrystal is small. The critical size of about 5 nm may vary with temperature or the type of ligand. Our proposed ligand mobility–controlled selective facet–arrested shape evolution may apply to other ligands and nanoparticle shapes.

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SUPPLEMENTARY MATERIALS

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Attribution of global glacier mass loss to anthropogenic and natural causes

Ben Marzeion,[1]* J. Graham Cogley,[2] Kristin Richter,[1] David Parkes[1]

The ongoing global glacier retreat is affecting human societies by causing sea-level rise, changing seasonal water availability, and increasing geohazards. Melting glaciers are an icon of anthropogenic climate change. However, glacier response times are typically decades or longer, which implies that the present-day glacier retreat is a mixed response to past and current natural climate variability and current anthropogenic forcing. Here we show that only 25 ± 35% of the global glacier mass loss during the period from 1851 to 2010 is attributable to anthropogenic causes. Nevertheless, the anthropogenic signal is detectable with high confidence in glacier mass balance observations during 1991 to 2010, and the anthropogenic fraction of global glacier mass loss during that period has increased to 69 ± 24%.

Although glaciers store less than 1% of global ice mass (*1*), their mass loss has been a major cause of sea-level rise during the 20th century (*2*). Glaciers are important regulators of the seasonal water cycle, providing meltwater during dry seasons in many regions of the world (*3*, *4*). Glacier retreat often leads to the destabilization of mountain slopes and the formation of unstably dammed meltwater lakes, increasing the risk of rockslides and catastrophic outburst floods (*5*). The worldwide retreat of glaciers over the past decades has therefore had many impacts on human societies, which should increase over the 21st century because of continued mass losses (*6*–*8*).

Even though warming has accelerated over recent decades (*9*), glaciers have contributed to sea-level rise during most of the 20th century with relatively constant mass loss rates (*2*, *6*, *10*). The mass loss during the first decades of the 20th century was presumably governed by the loss of ice at low altitudes, when glaciers retreated from their 19th-century maxima at the end of the Little Ice Age (*11*). Because glacier extent responds to changes in the glacier mass balance (MB) with a lag of decades to centuries (*12*–*14*), glaciers provide an opportunity to directly perceive long-term climate change, unobscured by interannual variability. For this reason, images of retreating glaciers have become widely publicized illustrations of anthropogenic climate change. At the same time, the lagged response of glacier extents to climate changes complicates the attribution of the observed changes to any particular cause, because glacier mass change at any time is in part an ongoing adjustment of the glacier to previous climate change. The global retreat of glaciers observed today started around the middle of the 19th century, coinciding with the end of the Little Ice Age (*10*), when the anthropogenic forcing of the climate system was very weak as compared to today (*15*). Given the response times of glaciers, it is therefore reasonable to hypothesize that glaciers at present are responding both to naturally caused climate change of past centuries and to the anthropogenic warming that has become stronger in recent decades. There is evidence that the recent mass loss of individual glaciers exceeds values expected from internal variability (*16*), and a rough estimate has been made of the influence of anthropogenic warming on global glacier mass loss (*17*), but the explicit attribution of observed changes of individual glaciers is also complicated by the dynamic response of glaciers' geometries to climate forcing, because internal variability alone may cause glacier changes of the magnitude observed since the end of the Little Ice Age (*18*).

Here we quantify the evidence for a causal link between anthropogenic climate forcing and observed glacier surface MBs, not of individual glaciers but of all the world's glaciers outside of Antarctica combined. We then attribute the global glacier retreat since 1851 to natural and anthropogenic causes. We use a model of global glacier evolution that treats the MB of each of the world's glaciers contained in the Randolph Glacier Inventory (RGI) (*19*, *20*) individually, including a simple parametrization of ice dynamics leading to glacier hypsometry change (*6*). Forced by observed climate (*21*, *22*), the glacier model has been independently validated against both annual surface MB observations (fig. S1) and observed, temporally accumulated volume changes of hundreds of glaciers (*23*), and has been used to reconstruct and project the global glacier mass change from 1851 to 2300 (*6*), based on climate reconstructions and projections from the Coupled Model Intercomparison Project phase 5 (CMIP5). See the supplementary materials for a comprehensive description of the model.

For each of 12 reconstructions of the global climate between 1851 and 2010, produced by general circulation models (GCMs) from the CMIP5 ensemble (see table S1 for the list of the experiments used), we reconstructed the area and volume of each glacier in 1851 (*6*). From this

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reconstructed glacier state, we modeled the evolution of each glacier forward in time. This forward model was run twice for each GCM: once subject to all known forcings (i.e., solar variability, volcanic eruptions, land-use change, anthropogenic aerosols, and greenhouse gas emissions; we call these model runs the FULL runs below), and once subject to only natural forcings (i.e., solar variability and volcanic eruptions; we call these model runs the NAT runs below). Figure 1A shows the ensemble mean and standard deviation of the global mean specific MBs for the FULL and NAT runs. Because the global mean specific MB interpolated from observations (*23*) (we call these OBS below) is available as pentadal means only (black lines in Fig. 1A), we determined the pentadal means of the model runs (thick solid lines in Fig. 1A). In order to determine whether the modeled glacier MBs are consistent with observed MBs, we calculated the confidence level of the difference between modeled and observed MBs for each pentad. High confidence in this difference (i.e., red shading in Fig. 1B) thus indicates model results that are inconsistent with observations.

Modeled MBs in both the FULL and NAT runs are negative over essentially the entire period considered. However, a difference emerges over the course of the 20th century: Although the MB of the NAT runs becomes less negative as glaciers retreat to higher altitudes, thus stabilizing their MBs, there is a clear trend toward more negative MBs of glaciers in the FULL runs after 1965. Modeled MBs in the FULL runs are generally consistent with observations during the entire period covered by the latter, whereas the NAT runs are inconsistent with observations for at least the four pentads spanning 1991 to 2010 (Fig. 1B). This means that the anthropogenic signal is detectable in observed MBs over these four pentads with high confidence, unaffected by the result that MBs would have been negative during this period even without anthropogenic climate forcing. The anthropogenic fraction of global specific glacier mass loss rates increased from −6 ± 35% during the period 1851 to 1870 to 69 ± 24% during the period 1991 to 2010 (Fig. 1C, uncertainties correspond to one ensemble standard deviation). Without anthropogenic influence, glaciers would have contributed 99 ± 36 mm to global mean sea-level rise during 1851 to 2010. With anthropogenic influence, this number increases to 133 ± 30 mm (Fig. 1D, uncertainties correspond to one ensemble standard deviation).

When global mean MBs over longer periods than pentads are considered, it becomes evident that the NAT runs are inconsistent with observations for any period spanning 5 to 50 years and ending in 2010 (Fig. 2). The FULL runs are generally consistent with observations (Fig. 1B), but the simulated MBs are more negative than the observations during 2001 to 2010 (Fig. 1A), resulting in a difference between FULL runs and observations above the 85% confidence level for periods spanning 5 to 15 years and ending in 2010 (Fig. 2). This difference is caused by the FULL MBs for Svalbard and the Russian Arctic, which are too negative as compared to the observations.

Glacier mass losses attributable to human activity (shown as a fraction in Fig. 1C) have increased nearly steadily since 1860. In Fig. 3 we plot the year-by-year anthropogenic global mean specific mass balance $MB_{ANTH} = MB_{FULL} - MB_{NAT}$ against the concurrent anthropogenic radiative forcing R (*24*), and find a sensitivity dMB_{ANTH}/dR of −209 ± 33 kg year^{-1} W^{-1} (uncertainty corresponds to the 95% confidence interval). This is about twice as much as a direct calculation based on the latent heat of fusion of ice would give (−94 kg year^{-1} W^{-1}), indicating that feedbacks and the spatial distribution of anthropogenic climate change play an important role.

On the regional scale, the increased signal from internal climate variability, and greater uncertainty of GCM results (*25*), reduce the detectability of the anthropogenic signal. Although there are some regions where the anthropogenic signal is detectable (i.e., FULL runs are consistent with observations, whereas NAT runs are inconsistent), there are also a number of regions where the FULL runs are not consistent with observations (Fig. 2). The anthropogenic signal is detectable with high confidence in Alaska, western Canada and United States, Arctic Canada north and south, Greenland (only peripheral glaciers and not the ice sheet are considered there), north Asia, central Europe, low latitudes, and New Zealand (9 out of 18 regions), and with lesser confidence in Iceland, Scandinavia, and central Asia north (3 out of 18 regions). In Svalbard, the Russian Arctic, the Caucasus and Middle East, and the southern Andes, the FULL runs are inconsistent with observations (4 out of 18 regions), and in central Asia south and west both FULL and NAT runs are consistent with observations (2 out of 18 regions). A closer look at those regions where our method fails reveals that in the Caucasus and Middle East and the southern Andes, both the FULL and NAT runs underestimate the mass losses (in both cases, the FULL runs are closer to observations than the NAT runs).

In Svalbard and the Russian Arctic, the FULL run overestimates the mass loss, whereas the

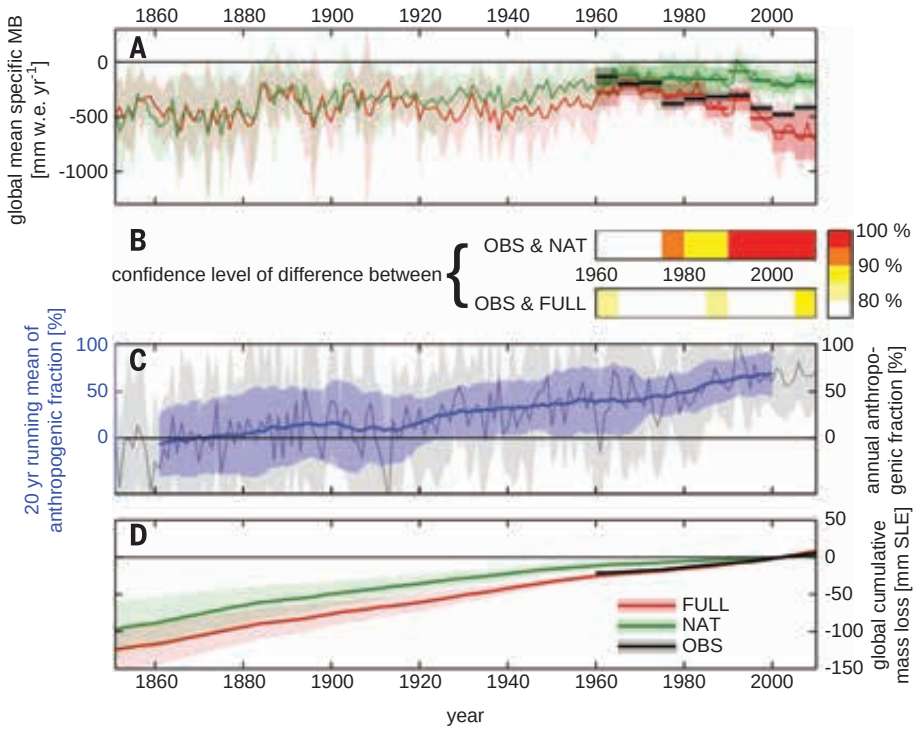

Fig. 1. Attribution of the anthropogenic signal in global mean glacier MBs. (**A**) Global mean specific MB time series (thin lines are the ensemble means, shading indicates one ensemble standard deviation) and pentadal means (thick lines are the ensemble means, shading indicates 1 SE; see the supplementary materials for the derivation of the error) are shown. Green, NAT results; red, FULL results; black, observations. (**B**) Confidence level of the difference between interpolated observations (OBS) updated from Cogley (2009) (*23*) and model results for the NAT and FULL models for each pentad. (**C**) Anthropogenic fraction of total glacier mass loss, annual values (gray), and running mean over 20-year periods (blue); the solid line is the ensemble mean; shading indicates one ensemble standard deviation. (**D**) Glacier contribution to global mean sea-level rise, relative to the mean of 1991 to 2010. Modeled results include modeled glacier area change; observations assume constant glacier area, as in the RGI (*19*) (the solid lines are the ensemble means; shading indicates one ensemble standard deviation).

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NAT run is consistent with observations (fig. S2). GCMs tend to have greater errors in this region than on global average (*25*), but they do not generally exhibit a stronger warming during summer months or reduced precipitation as compared to observations (*22*), which could explain too-negative modeled MBs. When we exclude calving glaciers from the observational data set (calving is not accounted for in the glacier model but does affect the observational estimate), the difference is reduced slightly, but not enough to lead to consistent results in these regions. Because validation of the glacier model on individual glaciers, as opposed to the regional mean, does not indicate a general underestimation of the modeled MBs in Svalbard (*6*), the reason for this regional inconsistency has to be related to the sampling of glacier MB observations (*26*), but ultimately remains unclear.

Because the glaciers are considerably out of balance with both modeled FULL and NAT climate at the beginning of the simulation period, it is not possible to distinguish between glacier mass losses caused by internal variability and natural forcing. In order to address this question, it would be necessary to identify the causes that led to the buildup of glacier mass during the Little Ice Age, a period not covered by the CMIP5 experiments. However, our results indicate that a considerable fraction of 20th-century glacier mass loss, and therefore also of observed sea-level rise, was independent of anthropogenic climate forcing. At the same time, we find unambiguous evidence of anthropogenic glacier mass loss in recent decades.

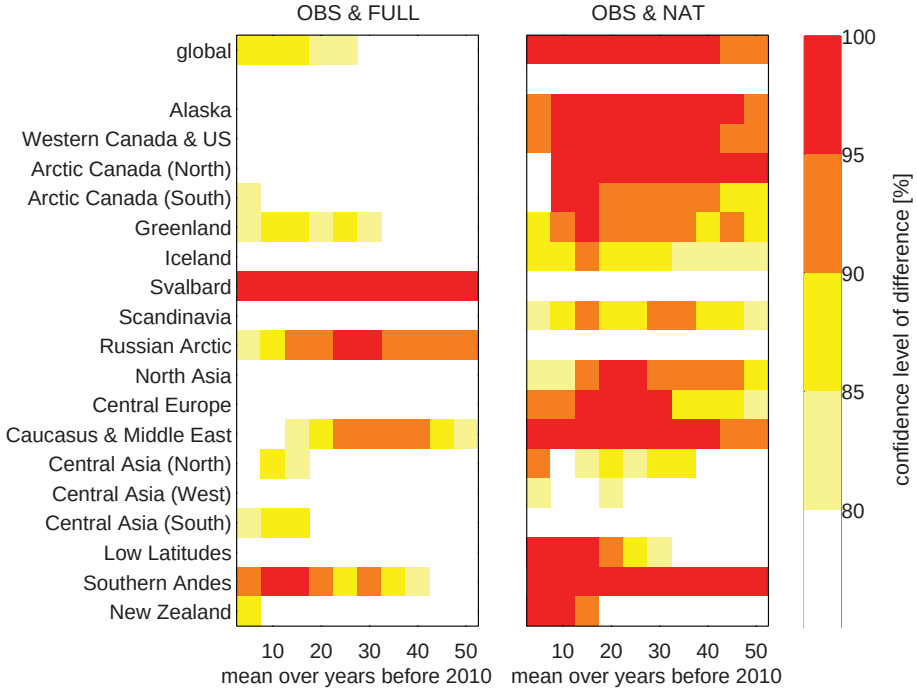

Fig. 2. Detection of the anthropogenic signal in global and regional glacier MBs over longer time intervals. Confidence levels of difference between observations (*23*) and model results for the NAT and FULL models for periods of different length ending in 2010 are shown. Regions are as defined in the RGI (*19*).

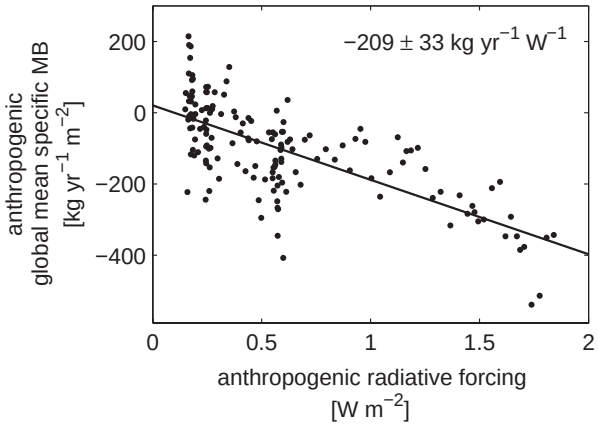

Fig. 3. Sensitivity of the instantaneous anthropogenic global mean specific MB to global mean anthropogenic radiative forcing. Annual values of MB_{ANTH} plotted against concurrent anthropogenic radiative forcing *R* (*24*) are shown. The Pearson correlation coefficient between the two is −0.71.

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SUPPLEMENTARY MATERIALS

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Attribution of global glacier mass loss to anthropogenic and natural causes
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Editor's Summary

Putting the heat on Mother Nature

Humans are now the biggest cause of glacier melting. Until recently, that was not true. Glaciers take a long time––decades to centuries––to respond to the environmental changes that control their sizes. They have been retreating gradually from the peak levels they reached in the middle of the 19th century, at the end of a 500-year-long cold period called the Little Ice Age. Marzeion *et al.* show that that has recently changed though, as climate warming has continued: Over the past 20 or so years, the anthropogenic contribution to glacial mass loss has increased markedly (see the Perspective by Marshall).

Science, this issue p. 919; see also p. 872

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nature geoscience

ARTICLES

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Centennial glacier retreat as categorical evidence of regional climate change

Gerard H. Roe[1]*, Marcia B. Baker[1] and Florian Herla[2]

The near-global retreat of glaciers over the last century provides some of the most iconic imagery for communicating the reality of anthropogenic climate change to the public. Surprisingly, however, there has not been a quantitative foundation for attributing the retreats to climate change, except in the global aggregate. This gap, between public perception and scientific basis, is due to uncertainties in numerical modelling, and the short length of glacier mass-balance records. Here we present a method for assessing individual glacier change based on the signal-to-noise ratio, a robust metric that is insensitive to uncertainties in glacier dynamics. Using only meteorological and glacier observations, and the characteristic decadal response time of glaciers, we demonstrate that observed retreats of individual glaciers represent some of the highest signal-to-noise ratios of climate change yet documented. Therefore, in many places, the centennial-scale retreat of the local glaciers does indeed constitute categorical evidence of climate change.

Alpine glaciers are consequential and captivating elements of the Earth system that feature prominently in the lives of nearby communities[1]. The nature of glacier motion was a research challenge for nineteenth-century physicists[2,3], and the late Holocene history of glacier margins has been a primary target of modern palaeoclimate science[4]. Consequently, the century-scale length history of several hundred glaciers is well known (for example, Fig. 1)[4,5]. Whilst glacier mass balance (that is, area-averaged accumulation minus ablation, $\equiv b$ (m yr^{-1})) is a more direct measure of climate[6,7] than glacier length, only a few dozen mass-balance records extend for more than two decades.

The century-scale, near-global retreat of glacier fronts seems improbable without some coordinating global climate change. However, the formal statistical assessment of the role of climate change in glacier retreat has been limited to the numerical modelling of three individual glaciers, each with only a single set of model parameters[8]; and to a comparison of the global aggregate glacier mass loss in forced and unforced integrations of global climate models[9].

By itself, any single glacier is a blunt statistical instrument. Each is a unique product of its local climate and landscape. Characteristic glacier-length response times of several decades[10] imply only a few independent degrees of freedom in a centennial record, resulting in poor statistical resolving power to evaluate a trend. In part because of these factors, the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) concluded only it was 'likely' that a 'substantial' part of glacier retreat is due to anthropogenic climate change, a much weaker attribution than for other metrics of climate change[11]. Here we introduce a method to combine glacier observations with the better-resolved local meteorological trends, which facilitates strong conclusions. The centennial-scale retreats of 37 widely dispersed glaciers have each necessarily required a climate change. And while the cause cannot be attributed purely from observations, the required climate changes are centennial-scale trends that are globally distributed.

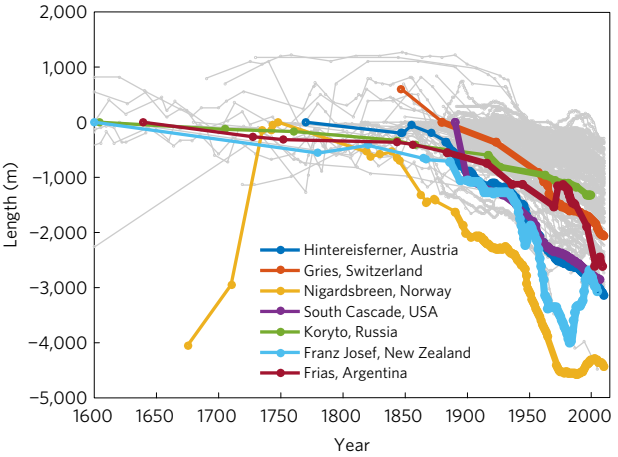

Figure 1. The global record of glacier lengths[5], for 158 glaciers with 20 or more individual observations (shown as dots). Coloured lines show the specific glaciers analysed in Fig. 4.

The signal-to-noise ratio as a metric of glacier change

We relate s_L, the signal-to-noise ratio of glacier length ($\equiv L$), to s_b, the signal-to-noise ratio of mass balance ($\equiv b$). Let ΔL be the change in length over some period of time, and let σ_L be the standard deviation in the absence of any climate trend. Then $s_L \equiv \Delta L/\sigma_L$. Likewise, $s_b \equiv \Delta b/\sigma_b$. We first establish that s_L is straightforwardly related to s_b, and that the relationship is insensitive to uncertainties in glacier parameters. The result is robust and depends only on the fundamental property that glaciers integrate mass balance on timescales of a few decades.

In a refinement of earlier models[12,13], previous work has shown that glacier flow on a sloping bed can be accurately emulated by a linear, third-order differential equation (Methods)[14]. Let $\Delta b(t_o)$ be the change in mass balance due to a linear trend applied over a

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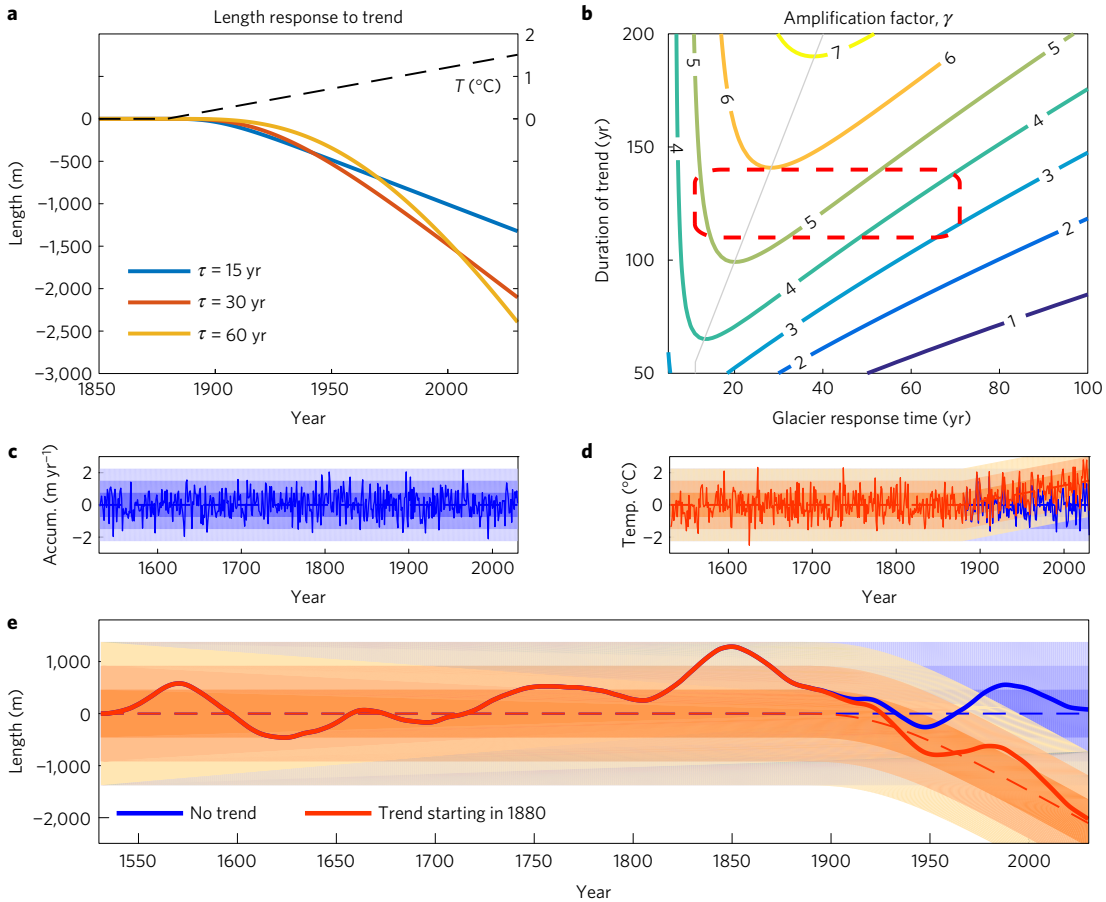

Figure 2. The response of idealized glaciers to climate. **a**, The response to a warming trend (dashed line, right axis) of three idealized glaciers with response times of $\tau = 15$, 30 and 60 yr (coloured lines, left axis). **b**, The amplification factor $\gamma(\tau, t_o)$, in the relationship $s_L = \gamma \cdot s_b$. The dashed red box covers the approximate range applicable to alpine glaciers. Thus, $\gamma \simeq 4$ to 6 for a wide range of the relevant parameter space. **c**, A 500-yr segment of synthetic, random white-noise accumulation ($\sigma_P = 0.75$ m yr^{-1}), shading denotes 1, 2 and 3σ ranges. **d**, As for **c**, but for melt-season temperature ($\sigma_T = 0.75$ °C), and with an imposed 1 °C-per-century warming trend beginning in 1880. The blue line and shading have no warming trend. **e**, Response of a glacier with $\tau = 30$ yr, $\beta = 180$. Due to the applied warming trend from 1880 to 2010, $\Delta L = -1{,}700$ m, $\sigma_L = 460$ m, giving $s_L = -3.7$. In these simulations, anomalies in temperature and mass balance are related via $b' = -\mu T'$, with $\mu = 0.65$ m yr^{-1} °C^{-1}.

period t_o. Our model yields $\Delta L(t_o) = \phi(t_o, \tau) \cdot \beta \cdot \Delta b(t_o)$, where τ and β are functions of glacier geometry. The glacier response time $\tau = -H/b_t$, where H is a characteristic ice thickness and b_t is the (negative) mass balance at the terminus[12]; β is the ratio of the glacier area to the product of H and the width across the terminus. The function $\phi(t_o, \tau)$ embodies the ice dynamics, and captures three distinct stages of adjustment: changes in interior ice thickness drive changes in ice flux at the terminus that, in turn, drive changes in glacier length[12,14]. τ is central to a glacier's response: Fig. 2a shows $\Delta L(t)$ for a warming trend of 1 °C per century, for three glaciers with different τ (and fixed β). Physically, τ controls how quickly a glacier responds to climate variations and also how strongly the glacier is restored to equilibrium[12–14]: small-τ glaciers respond quickly but are less sensitive, whereas large-τ glaciers respond slowly but are ultimately more sensitive. These fundamental trade-offs are independent of the model used (see Supplementary Information), and mean that a century or so after a climate trend commences, the amount of retreat is relatively insensitive to several-fold variations in τ (Fig. 2a).

Our model, and all equivalent models, also yield $\sigma_L \propto \beta \cdot \sigma_b$ (Methods). Thus, s_L can be written as:

$$s_L = \gamma(t_o, \tau) \cdot s_b \qquad (1)$$

$\gamma(t_o, \tau)$ is an amplification factor that depends only on the duration of the trend and the glacier response time. The counteracting tendencies of initial responsiveness versus long-term sensitivity mean that $\gamma(t_o, \tau)$ is quite insensitive to τ. For example, for a 130-yr trend, glacier length is a fourfold to sixfold amplifier of the mass-balance signal-to-noise ratio, across a wide range of response times (Fig. 2b). The relative constancy of γ is key to estimating s_L from meteorological observations. Note both ΔL and σ_L are proportional to the parameter β and so it drops out of s_L.

The relationship between s_L and s_b can be illustrated with a synthetic example for typical climate trends and variability. Assume a 1 °C-per-century increase in melt-season (June–September) temperature ($\equiv T$) beginning in 1880, no trend in annual-mean precipitation ($\equiv P$), and white-noise interannual variability (consistent with observations[7]) characterized by $\sigma_T = 0.75$ °C and $\sigma_P = 0.75$ m yr^{-1}, respectively (Fig. 2c,d). A simple mass-balance model is $b' = P' - \mu T'$, where μ is a melt factor ($= 0.65$ m yr^{-1} K^{-1})[15], and primes denote fluctuations about the long-term mean. After 130 yr of the imposed trend, $s_b = -0.65$. For $\tau = 30$ yr and $\beta = 180$, we get $\Delta L = -1{,}700$ m and $\sigma_L = 460$ m (Fig. 2e). Thus, the retreat is approximately three-and-a-half standard deviations ($s_L = \Delta L/\sigma_L \simeq -3.5$), consistent with an amplification factor of $\gamma \simeq 5.7$ (equation (1) and Fig. 2b).

An application to Hintereisferner, Austria

We next present the steps of our analysis for Hintereisferner in the Austrian Alps (Fig. 1). Applying least-squares regression for the

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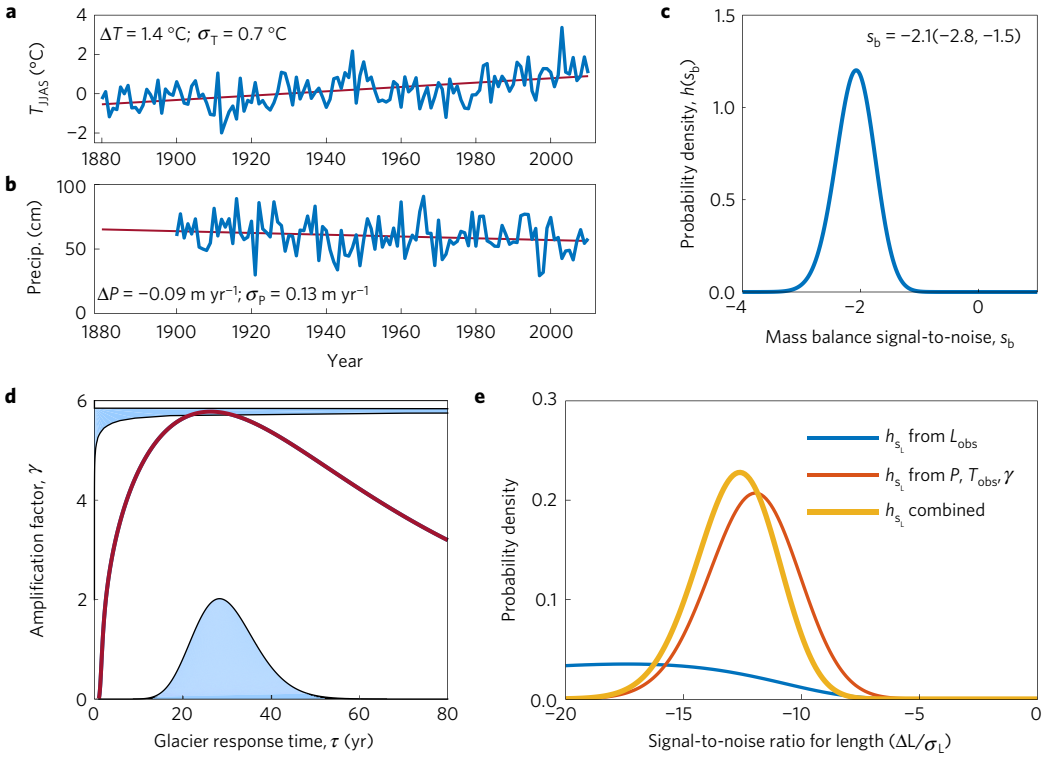

Figure 3 | Analysis for Hintereisferner (Austrian Alps, 46.8° N, 10.8° E). a, Melt-season (June–September) temperature from the Berkeley Earth data set of gridded station observations[17]. The best-fit trend, the change since 1880 and the standard deviation are also shown. **b**, As for **a**, but from the Legates and Willmot data set of gridded annual-mean precipitation[18], with the trend extrapolated to 1880. **c**, The PDF of the signal-to-noise ratio for mass balance, s_b (equation (2)), with median and 95% bounds also given. **d**, The blue shading on the *x* axis shows the PDF of uncertainty in glacier response time, τ; the red curve shows the relationship between τ and the amplification factor, γ, for a 130-yr trend; the blue shading on the *y* axis shows the PDF for γ that results from the PDF for τ being projected onto the y axis via the red line. **e**, PDFs of length signal-to-noise ratio, s_L, from different methods: blue, s_L from observations of *L*; red, s_L from *T*, *P* observations and the amplification factor γ (that is, equation (1)); orange, combined PDF using Bayes' theorem.

period 1880–2010, the glacier retreated 2,800 m with a standard deviation of 130 m about that trend. However, there are only three effective degrees of freedom in the record (Methods), so neither ΔL nor σ_L is well constrained. Consequently, the probability density function (PDF) of their ratio ($\equiv h_{s_L}|^{L_{obs}}$) is very broad (Fig. 3e and Methods): while it is extremely unlikely (<1%) that $s_L > 0$, one cannot rule out the possibility its magnitude is very large (that is, $s_L < -20$). In other words, there is not much information about s_L from the glacier length alone.

An independent approach to calculating s_L uses equation (1). To that end, we build a simple mass-balance model using long-duration, gridded instrumental observations[16,17] of *T* and *P*, scaled by the observed variability of the much shorter winter (b_w) and summer (b_s) mass-balance records[7,18]:

$$b'(t) = b'_w(t) + b'_s(t) = \sigma_{b_w}\frac{P'(t)}{\sigma_P} + \sigma_{b_s}\frac{T'(t)}{\sigma_T} \qquad (2)$$

where $\sigma_{(x)}$ is the standard deviation of *x*. Thus, the modelled mass balance matches the observed variance, and combines the observed signal-to-noise ratios of *P* and *T*. Normalizing by σ_P accounts for orographic-precipitation effects since fractional variations in precipitation are relatively uniform in mountainous areas. Between 1880 and 2010, Hintereisferner experienced strong warming: $\Delta T = +1.4\,°C$, with $\sigma_T = 0.7\,°C$ (Fig. 3a); and some drying: $\Delta P = -0.09\ m\,yr^{-1}$, with $\sigma_P = 0.13\ m\,yr^{-1}$ (Fig. 3b, extrapolated from a 100-yr record). Observations from the adjacent Vernagtferner[18] give $\sigma_{b_w} = 0.22\ m\,yr^{-1}$, $\sigma_{b_s} = 0.42\ m\,yr^{-1}$. Thus, from equation (2), the median (and 95% bounds) for $s_b = -2.1(-2.8, -1.5)$ (Fig. 3c and Methods): s_b is negative but with some uncertainty. Although the detrended $b'(t)$ is consistent with white noise, we evaluate the potential impact of climatic persistence in the Supplementary Information.

For Hintereisferner[19], $H \simeq 170$ m and $b_t \simeq -6\ m\,yr^{-1}$, giving $\tau \simeq 30$ yr. Formulae for τ vary in the literature[12,13], so we allow broad uncertainty; we represent its PDF by a gamma distribution with $\sigma_\tau = \tau/4$. Figure 3d shows this nonetheless results in a very narrow PDF of γ, centred on $\gamma \simeq 5.6$. Hintereisferner thus acts as a near-optimal amplifier of the climate signal-to-noise ratio. From equation (1) the PDFs of γ and s_b can be combined to give a second PDF for s_L ($\equiv h_{s_L}|^{T,P_{obs}}$), based only on instrumental observations and the approximately several-decade response time of this glacier (Fig. 3e). This PDF rules out extremely negative s_L (for example, $s_L \leq -20$) as inconsistent with observed climate trends (that is, $s_b \simeq -2$) and the roughly sixfold amplification by the glacier length.

These two PDFs of s_L, one based on observations of *L*, and one based on γ and s_b, are independent. Therefore, they can be combined using Bayes' theorem (Methods)[20]. The resulting median (and 95% bounds) is $s_L = -13(-17, -10)$ (Fig. 3e). This is an extraordinarily large magnitude compared with other documented climate metrics. For comparison, the local ΔT near Hintereisferner is 2σ, and the global-mean, annual-mean ΔT trend over the same period is 6σ.

The result that $\Delta L \approx -13\sigma_L$ must not itself be directly equated to statistical significance because length variations are correlated in time. To proceed, we solve for the PDF of σ_L from the relation $\sigma_L = \Delta L|^{obs}/s_L$, using the known observed retreat and the combined PDF for s_L. For Hintereisferner, we find σ_L (and 95% bounds) = 220(170, 280) m. Although this estimate depends primarily on observations, it is consistent with calculations from modelling

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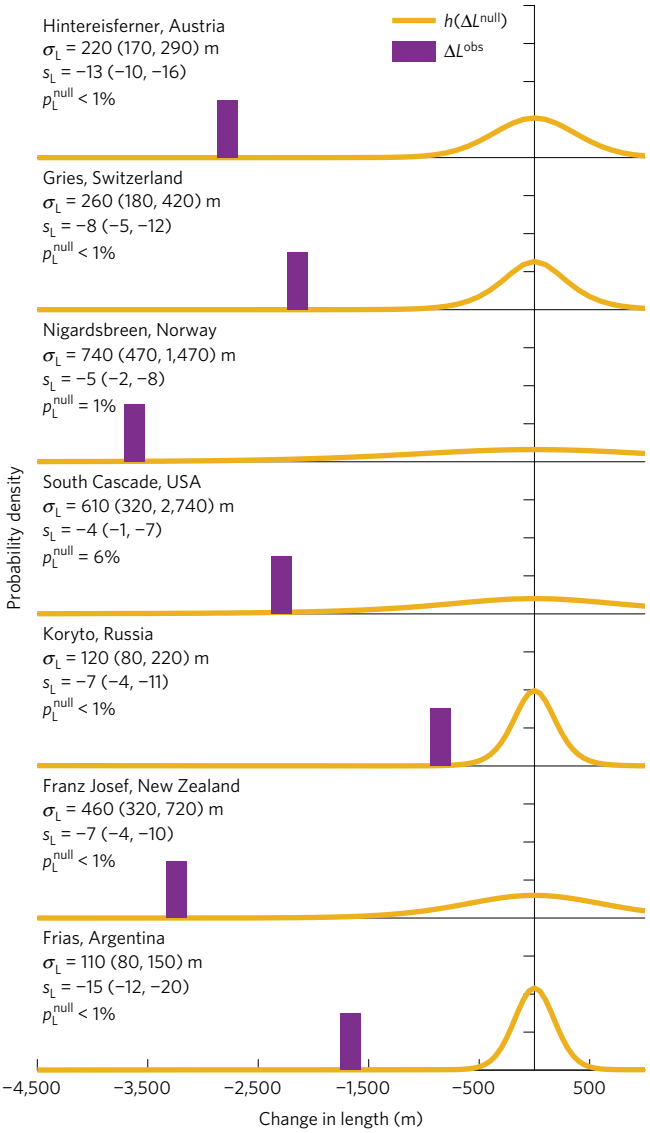

Figure 4. Analysis of glacier retreat from around the world (see Fig. 1). For each glacier, the PDF for ΔL in any 130-yr period with no climate change is shown, and compared with the observed retreat represented by the vertical bar. Also given is the estimated standard deviation and signal-to-noise ratio (with 95% bounds), and the p value for the null hypothesis—the likelihood that the observed retreat occurred in the absence of a climate change. All PDFs have areas normalized to 1. See Supplementary Information for 30 other glaciers worldwide, and a full table of the analyses.

(Methods). Finally, we test against a null hypothesis of no climate change. Using equation (1), the probability distribution of a given ΔL occurring in any 130-yr period without climate change comes from combining the PDFs for each of the terms on the right-hand side of: $\Delta L|^{null} = \sigma_L \cdot \gamma \cdot s_b|^{null}$, where the PDF for $s_b|^{null}$ comes from the detrended mass-balance observations (Methods). We find the probability that the observed retreat comes from the null distribution is minuscule ($p_L^{null} = 0.001\%$, Fig. 4a); it is thus highly significant and must be attributed to a climate change. In general, the statistical significance of the glacier retreat may be larger or smaller than that of other local climate metrics. For example, although the global aggregate of the much shorter duration glacier mass-balance observations is negative and significant at the 5% level[7], only 17/48 and 4/48 of the individual summer and winter mass-balance records longer than 10 years exhibit significant trends (all negative)[7]. For Hintereisferner, s_L and the statistical significance are so large because of the observed drying in addition to the observed warming (Fig. 3a,b), and because the Bayesian step combining PDFs with length observations indicates a slightly more negative s_L (Fig. 3e).

An evaluation of glaciers worldwide

The foregoing analysis can be applied to any glacier with a long length record and known mass-balance variability. The results for seven widely distributed glaciers (Fig. 1) are shown in Fig. 4. Although the size of the retreats vary by more than a factor of five, for each glacier it is very unlikely that it could have occurred without climate forcing. The least significant retreat, $p_L^{null} = 6\%$, is South Cascade Glacier, which has a small median $s_b \simeq -0.7$, resulting from a relatively small warming in a maritime climate where winter mass-balance variability exceeds that in summer[7] (Supplementary Information).

We have analysed a total of 37 glaciers worldwide, selecting those with the longest mass-balance and length records. All steps and results are detailed in the Methods and Supplementary Information. In several cases, nearby mass-balance records were used, and when length observations were too sparse to characterize the degrees of freedom, a uniform negative-definite $h_{s_L}|^{L_{obs}}$ was assumed, consistent with the observed retreat (that is, $\Delta L < 0$) of all evaluated glaciers (Fig. 1 and Supplementary Information), and the fact that σ_L is positive. For the 37 glaciers, the median values of s_L and σ_L range from −2 to −15 and from 120 m to 750 m, respectively. Our analyses represent an approximately tenfold increase in the number of glaciers for which σ_L has been estimated; three of our selected glaciers have previous model-based estimates of σ_L that lie within our observation-based ranges[8,14]. Such estimates are valuable for putting reconstructions of past Holocene glacier fluctuations into context[15]. We note that the response of glacier length to climate trends and to natural variability form complementary pairs: glaciers that are sensitive to climate change also tend to have higher variability.

For 21 of the 37 glaciers, $p_L^{null} \leq 1\%$. Adopting IPCC nomenclature, it is thus 'virtually certain' that the retreat of each of these individual glaciers required a climate change. A further seven have $p_L^{null} \leq 5\%$. The least significant, Rabots Glacier in northern Sweden, has $p_L^{null} = 11\%$. Thus, for all but one glacier, it is 'very likely' (≥90%, IPCC) their retreat is attributable to climate change.

These calculations and uncertainty estimates can undoubtedly be refined and improved by more sophisticated mass-balance models and by detailed numerical case studies with explicit valley geometry, and of course our analyses do not, on their own, speak to the cause of the required climate change. However, the decadal response time of glaciers means their centennial retreat is predominantly a response to the twentieth-century climate trends rather than being a dynamical recovery from any antecedent conditions, such as the putative Little Ice Age[21]. The fundamental principle evinced here—that glaciers act as several-fold amplifiers of the signal-to-noise ratio of local climate trends—is robust. The principle is not limited to glaciers. Any component of the climate system with a decadal timescale will damp high-frequency variations and integrate centennial-scale trends. However, glaciers are perhaps unique in combining a decadal timescale with a strong sensitivity and simple dynamical response to temperature, creating near-maximum signal-to-noise ratios for centennial-scale climate change (Fig. 2b). In combination with climate and glacier observations, this has enabled our quantification of just how far individual glaciers have been driven from their pre-industrial states by climate change.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

G.H.R., M.B.B. and F.H. planned the analyses, which G.H.R. performed. All authors contributed to the interpretation of the results and to writing the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.H.R.

Competing financial interests

The authors declare no competing financial interests.

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Methods

A three-stage model. A refinement of earlier analytical glacier models[12,13] was developed in ref. 14, and showed that numerical models of ice flow on a constant slope could be accurately emulated by a third-order linear differential equation:

$$\left(\frac{\mathrm{d}}{\mathrm{d}t}+\frac{1}{\epsilon\tau}\right)^3 L' = \frac{\beta}{\epsilon^3\tau^2}b'(t) \tag{3}$$

where $L'(t)$ is the length perturbation from some long-term, mean-state position, driven by mass-balance fluctuations, $b'(t)$. $\tau=-H/b_t$, where H is a characteristic thickness and b_t is the (negative) mass balance at the terminus; $\beta=A_{tot}/(wH)$, where A_{tot} is the mean-state glacier area and w is the characteristic width at the terminus; and $\epsilon=1/\sqrt{3}$. Reference 14 showed that equation (3) captures three essential stages of glacier adjustment: changes in interior ice thickness drive changes in ice flux at the terminus that, in turn, drive changes in glacier length. Equation (3) has analytic solutions that facilitate efficient analyses over a wide range of parameter space.

Response to a trend. Consider a linear trend in mass balance commencing at $t=0$. Let $\Delta b(t_o)$ be the resulting change in mass balance after a time t_o has elapsed. The exact solution of equation (3) for the resulting length change, $\Delta L(t_o)$, is:

$$\Delta L(t_o)=\phi(t_o,\tau)\cdot\beta\cdot\Delta b(t_o) \tag{4}$$

where

$$\phi(t_o,\tau)=\tau\left[\frac{3}{r}\left(\mathrm{e}^{-r}-1\right)+1+\mathrm{e}^{-r}\left(\frac{r}{2}+2\right)\right] \tag{5}$$

and $r=t_o/\epsilon\tau$. We note that $\phi(t_o,\tau)\to\frac{\tau}{t_o}(t_o-3\epsilon\tau)$ in the limit that $t_0\gg\epsilon\tau$. Equation (4) is used to calculate the curves in Fig. 2a.

Glacier-length variance. Consider stochastic white-noise interannual fluctuations in mass balance (that is, random, year-to-year variability due to the vagaries of the weather, with no year-to-year persistence). Let the standard deviation of such fluctuations be σ_b. Such mass-balance fluctuations drive variability in glacier length, characterized by a standard deviation σ_L. Ref. 14 shows that:

$$\sigma_L=\beta\cdot\psi(\tau)\cdot\sigma_b \tag{6}$$

where

$$\psi(\tau)=\tau\left\{\frac{(1-\kappa)(1+4\kappa^2+\kappa^4)}{(1+\kappa)^5}\right\}^{\frac{1}{2}} \tag{7}$$

with $\kappa=1-(\Delta t/\epsilon\tau)$ and $\Delta t=1$ yr. We note that $\psi(\tau)\to(3\tau\Delta t/16\epsilon)^{1/2}$ in the limit of $\epsilon\tau\gg\Delta t$.

Estimated variance for Hintereisferner. Taking Hintereisferner in the Austrian Alps as an example, reasonable values for parameters are[19]: $A_{tot}\simeq10.5\,\mathrm{km}^2$, $w\simeq400$ m, $H\simeq170$ m; $b_t\simeq-6.5\,\mathrm{m\,yr^{-1}}$, giving $\beta\simeq150$ and $\tau\simeq30$ yr. With $\sigma_b\simeq0.5\,\mathrm{m\,yr^{-1}}$ from the adjacent Vernagtferner[7,18], equation (6) yields $\sigma_L\simeq230$ m. This value is close to the central estimate of σ_L made from observed retreat of Hintereisferner and local climate trends: $\sigma_L\simeq220$ m (Fig. 4).

Signal-to-noise ratio, s_L. Therefore, for a climate trend superposed on natural interannual variability, the signal-to-noise ratio for glacier length, s_L, can be formed from equation (4) divided by equation (6):

$$s_L=\frac{\Delta L}{\sigma_L}=\frac{\phi(t_o,\tau)}{\psi(\tau)}\cdot\frac{\Delta b(t_o)}{\sigma_b}=\gamma(t_o,\tau)\cdot s_b \tag{8}$$

Contours of $\gamma(t_o,\tau)$ are plotted in Fig. 2b.

Signal-to-noise ratio from length observations. We considered glacier records from a compilation of 471 glacier-length histories worldwide[5]. The data set uses Stineman interpolation in between individual length observations to produce annual time series, although our results are not sensitive to the interpolation method. We selected 37 glaciers in total (in each of five regions—see Supplementary Information), and focus on the period 1880 to 2010. The main criteria in selecting glaciers were long mass-balance records and a broad geographic distribution. However, we also preferentially selected glaciers with near-continuous length observations, although for some regions such as Asia and South America, this criterion could not always be met.

The signal-to-noise ratio is given by $s_L=\Delta L/\sigma_L$, where ΔL is the change in length and σ_L is the standard deviation of the variability about that trend. We estimate s_L from least-squares linear regression. Let $h_{s_L}(s_L)|^{L_{obs}}$ be the probability density function (PDF) of s_L, and let $\overline{\Delta L}$ and $\overline{\sigma_L}$ be the central estimates of ΔL and σ_L, respectively. From ref. 22, and the standard formulae for uncertainties in regression parameters[23] applied to glacier trends[24], it can be shown that:

$$h_{s_L}(s_L)|^{L_{obs}}=\sqrt{\frac{\nu-1}{12}}\,\mathcal{F}\left(\sqrt{\frac{\nu-1}{12}}s_L,\nu-1,\frac{\overline{\Delta L}}{\overline{\sigma_L}}\sqrt{\frac{\nu-1}{12}}\right) \tag{9}$$

where $\mathcal{F}(x,\nu-1,\mu)$ is a non-central t-distribution of the variable x with $\nu-1$ degrees of freedom, and non-centrality parameter μ (refs 22,24). The formula in equation (9) was verified in Monte Carlo simulations of time series with stipulated trends added to random realizations of noise.

Degrees of freedom in a record. We estimate the number of degrees of freedom, ν, in the glacier record following a procedure recommended in ref. 23. We fit a third-order autoregressive process to the length data[14,23,25] and calculate the associated autocorrelation function, $r(\tau)$. The effective degrees of freedom are then given by:

$$\nu=\frac{n\Delta t}{\Delta t+2\int_0^\infty r(\tau)\mathrm{d}\tau} \tag{10}$$

where n is the number of years in the record and $\Delta t=1$ yr. The number of degrees of freedom in the length observations ranges from <1 up to ~6. Low degrees of freedom yield broad distributions for $h_{s_L}|^{L_{obs}}$ (for example, Fig. 3e), so that the most important information from the length observations is only that s_L is not positive. When this method identifies $\nu\leq1$, or when the length records are sparse, $h_{s_L}|^{L_{obs}}$ cannot be calculated in this way. We instead stipulate a uniform negative-definite $h_{s_L}|^{L_{obs}}$, consistent with the observed retreat (that is, $\Delta L<0$) of all glaciers analysed and the fact that σ_L is positive definite (see also Supplementary Information). Our second method for calculating s_L (described below) uses climate observations with many more degrees of freedom, which produces a much narrower PDF (for example, Fig. 3e). When the two PDFs are combined, the narrower PDF dominates (Fig. 3e), and so our results and conclusions are not sensitive to the estimate of ν.

Signal-to-noise ratio from climate observations and glacier amplification factor. The second method for calculating s_L is to use the relationship from equation (8):

$$s_L=\gamma(t_o,\tau)\cdot s_b \tag{11}$$

Calculating s_b and its persistence. As described in the main text, the mass-balance model is:

$$b'(t)=b'_w(t)+b'_s(t)=\sigma_{b_w}\frac{P'(t)}{\sigma_P}+\sigma_{b_s}\frac{T'(t)}{\sigma_T} \tag{12}$$

Values of P' (annual mean) come from the Legates and Willmot data set[17]. Values of T' (June to September in the Northern Hemisphere extratropics, December to March in Southern Hemisphere extratropics; annual mean in the tropics) come from the Berkeley Earth data set[16]. The data were taken from the nearest land grid point to each glacier's location. The data sets were chosen for their high spatial resolution, but alternative data sets show similar trends.

The PDF of s_b ($\equiv h_{s_b}$) is calculated using the same non-central t-distribution as equation (9):

$$h_{s_b}(s_b)|^{T,P_{obs}}=\sqrt{\frac{\nu-1}{12}}\,\mathcal{F}\left(\sqrt{\frac{\nu-1}{12}}s_L,\nu-1,\frac{\overline{\Delta b}}{\overline{\sigma_b}}\sqrt{\frac{\nu-1}{12}}\right) \tag{13}$$

Here, the degrees of freedom are also calculated by fitting an autoregressive model to $b'(t)$. Only 3 out of the 37 glaciers analysed have a mass-balance time series that indicates any persistence (documented in the Supplementary Spreadsheet), with most being well characterized by white noise, consistent with mass-balance observations[7,26]. Thus, for almost all of the records, the degrees of freedom are equal to the number of years in the record. The majority of the mass-balance trends are dominated by trends in summer mass balance due to the melt-season temperature trends, which is also seen in the much shorter records of actual glacier mass balance[7].

Calculating the PDF of γ from the PDF of τ. The central estimate of τ comes from the relationship $\tau=-H/b_t$. For each glacier, the source references for the characteristic thickness H and terminus ablation rate b_t are given in the Supplementary Spreadsheet. For the PDF of uncertainty in τ ($\equiv h_\tau(\tau)$) we take a gamma distribution (ensuring τ is positive definite), with a standard deviation of $\tau/4$ (Fig. 3d). Thus, the 95% uncertainty bounds on τ (that is, $\pm2\sigma$) are equal to τ itself—a broad and thus conservative estimate of the uncertainty.

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The PDF of $\gamma(t_o, \tau)$ ($\equiv h_\gamma$) comes from equation (8), and applying the relationship:

$$h_\gamma(\gamma) = \frac{h_\tau(\tau)}{\partial\gamma/\partial\tau} \tag{14}$$

For our analyses $t_o = 130$ yr (1880 to 2010). The nature of γ is such that even very broad PDFs in τ map onto narrow PDFs of γ (Fig. 3d).

The PDF of s_L. Finally, the PDF of s_L ($\equiv h_{s_L}(s_L)|^{T,P_{obs}}$) comes from combining h_γ and h_{s_b}. The probability that s_L lies between any given value s_L and $s_L + ds_L$ is given by:

$$h_{s_L}(s_L)\mathrm{d}s_L = \sum \left(h_\gamma(\gamma)\mathrm{d}\gamma \cdot h_{s_b}(s_b)\mathrm{d}s_b \right. \tag{15}$$

where the sum is taken over all possible pairs (s_b, γ) for which $s_b \cdot \gamma = s_L$. Using $\mathrm{d}s_b/\mathrm{d}s_L = 1/\gamma$, and taking the limits that $\mathrm{d}s_L, \mathrm{d}\gamma, \mathrm{d}s_b \to 0$, the sum becomes an integral:

$$h_{s_L}(s_L)|^{T,P_{obs}} = \int_0^\infty \left(h_\gamma(\gamma) \cdot h_{s_b}(s_L/\gamma) \cdot \frac{1}{\gamma} \cdot \mathrm{d}\gamma \right. \tag{16}$$

In other analyses in this study, the PDFs for all variables that are the product or ratio of two other variables are generated in a similar fashion. Where noted, the PDFs generated in this way have been verified with Monte Carlo simulations.

Combining the PDFs for s_L using Bayes' theorem. $h_{s_L}|^{L_{obs}}$ and $h_{s_L}|^{T,P_{obs}}$ are independent and so can be combined using Bayes' theorem to yield an updated, posterior PDF for s_L. We regard $h_{s_L}|^{L_{obs}}$ as the prior PDF that is updated by new information from the observed s_b. $h_{s_L}|^{T,P_{obs}}$ is equivalent to the likelihood function $\mathcal{L}(s_L|s_b)$, the likelihood of s_L given the new information s_b (ref. 20). For glaciers whose length history is too sparse (meaning if there are temporal gaps in the observations that are comparable to τ) or if the degrees of freedom are less than one, we stipulate an uninformative, flat prior for $h_{s_L}|^{L_{obs}}$ that is negative definite: h_{s_L} = constant for $s_L < 0$, and $h_{s_L} = 0$ otherwise. This is consistent with the observed negative ΔL of all glaciers analysed and the fact that σ_L is positive definite (see also Supplementary Information). Then the posterior PDF for s_L is given by:

$$h_{s_L}(s_L)|^{post} = k \cdot h_{s_L}(s_L)|^{L_{obs}} \cdot h_{s_L}(s_L)|^{T,P_{obs}} \tag{17}$$

where k is a normalization constant independent of s_L. An example of $h_{s_L}(s_L)|^{post}$ for Hintereisferner is shown in Fig. 3e.

Estimating σ_L from s_L. We estimate the PDF of σ_L ($\equiv h_{\sigma_L}$) from the relationship:

$$\sigma_L = \frac{\overline{\Delta L}}{s_L} \tag{18}$$

using $h_{s_L}|^{post}$ (that is, equation (17)) and the fact that ΔL is well constrained from observations.

Generating the PDF of the null hypothesis $p_L|^{null}$. We evaluate the observed glacier retreat against a null hypothesis of no climate change. For no climate trend the PDF of s_b ($\equiv h_{s_b}|^{null}$) is governed by the standard Student's t-distribution centred on zero[24]. That is, equation (13) with $\overline{\Delta b} = 0$. Thus, the PDF of the null hypothesis for s_L, $h_{s_L}|^{null}$, is calculated from the relationship $s_L = \gamma \cdot s_b$ and combining h_γ and $h_{s_L}|^{null}$.

Finally, we have $\Delta L = \sigma_L \cdot s_L$, and so the PDF of the null hypothesis for ΔL ($\equiv h_{\Delta L}|^{null}$) comes from combining h_{σ_L} and $h_{s_L}|^{null}$. We confirmed the validity of our calculations of $h_{\Delta L}|^{null}$ by Monte Carlo methods: generating a PDF of ΔLs from 10,000 130-yr integrations of the three-stage glacier-length model driven by climate variability with no trend.

Examples for $h_{\Delta L}|^{null}$ are shown in Fig. 4 and in Supplementary Figs 3–8. Following the standard approach, we determine the statistical significance of a glacier's retreat by calculating the probability, $p_L|^{null}$, that a ΔL could be consistent with the null hypothesis and yet lie beyond the observed retreat.

Code availability. The three-stage glacier model code is available from: http://earthweb.ess.washington.edu/roe/GerardWeb/Home.html. All analyses were performed by implementing the equations presented in the paper, for the data sets documented above.

Data availability. The following data sets were used in this study: glacier mass balance from: http://dx.doi.org/10.5904/wgms-fog-2014-09; glacier mass-balance analysis from: doi:10.1007/s00382-016-3253-x; glacier-length records from: http://www.the-cryosphere.net/8/659/2014/tc-8-659-2014-supplement.zip; Legates and Willmott precipitation data available from: http://www.esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html; Berkeley Earth temperature data available from: http://www.berkeleyearth.org/data. Other glacier parameters were taken from studies cited in the paper, and are documented in the Supplementary Information and in an accompanying spreadsheet.

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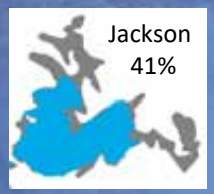
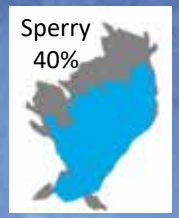
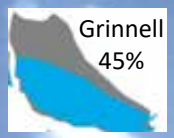
Losing a Namesake

Jackson Glacier, seen here from several miles away, has lost 41% of its area since 1966. In 1850 there were about 150 glaciers throughout the park, but today only 26 remain. Using a combination of historic maps and satellite imagery, scientists mapped these remaining glaciers. Check out the way glacier area changed. Retreat varied between individual glaciers, but the overall pattern is the same: Glaciers in Glacier National have shrunk, quite dramatically in some cases. This is consistent with the retreat of glaciers world wide, much of which is due to human-caused climate change.

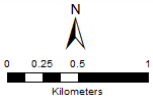




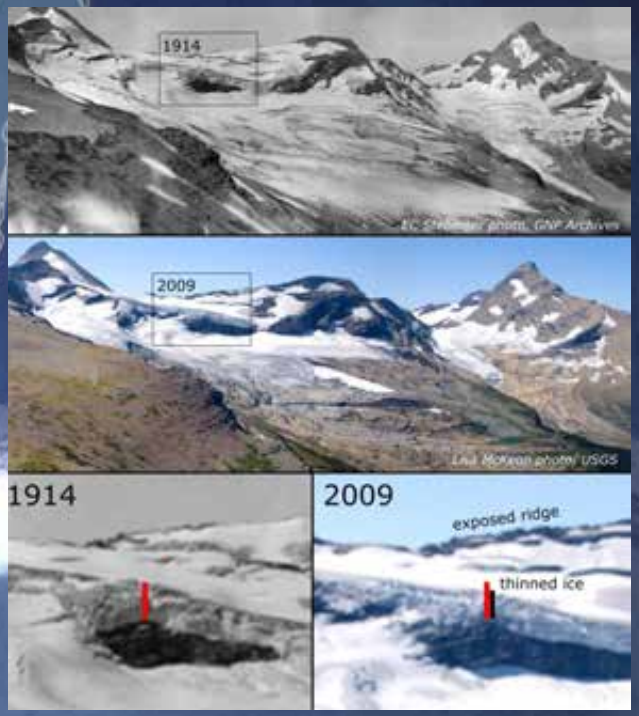


Order glaciers largest to smallest?
North to south?
Alphabetically?

1966 Glacier Extent



2015 Glacier Extent



Glaciers in 3D | The area change figures to the left only show two dimensions of glacier change, but in reality glaciers are massive and three dimensional. Look closely at the photos of Blackfoot and Jackson Glaciers in 1914 and 2009. Can you spot how the glacier has thinned?

INSIGHTS

PERSPECTIVES

CLIMATE CHANGE

Saying goodbye to glaciers

Glacier volume is shrinking worldwide, with wide-ranging implications for society

By **Twila Moon**

Global glacier volume is shrinking. This loss of Earth's land ice is of international concern. Rising seas, to which melting ice is a key contributor, are expected to displace millions of people within the lifetime of many of today's children. But the problems of glacier loss do not stop at sea level rise; glaciers are also crucial water sources, integral parts of Earth's air and water circulation systems, nutrient and shelter suppliers for flora and fauna, and unique landscapes for contemplation or exploration.

Finding that ice sheets can respond to climate change on subannual to decadal time scales, glaciology research surged in the early 21st century. Scientists now study the world's glaciers at many scales, from centimeter-scale in situ measurements to worldwide satellite-based monitoring campaigns.

Field studies facilitate detailed spatiotemporal sampling and deployment of coincident measurement suites, such as Global Positioning System (GPS), weather stations, seismometers, time-lapse cameras, and radar instruments. The results elucidate glacier hydrology, subsurface environments, and glacier dynamics on time scales of minutes to months. Aerial surveys cover inaccessible regions such as crevassed zones and even help with data acquisition between satellite missions.

To cover regions as large as ice sheets, space-borne satellite data are indispensable. Gravity-measuring satellites help estimate ice volume variations, altimetry satellites detect changing surface elevations, and optical and radar imaging satellites measure ice motion, monitor glacier advance and retreat, and observe surface properties, including melt. Growing in situ and satellite archives, along with glacier and ice sheet reconstruction efforts, are beginning to provide the longer records needed to separate glacier "climate" from glacier "weather" (*1*). The results from this surge in data and scientific effort point clearly to rapid and largely irreversible ice loss.

DISAPPEARING BEFORE OUR EYES

One of the most visible worldwide trends is glacier retreat. Photographs and aerial and satellite images of glaciers show consistent, substantial, and anomalous retreat from the Antarctic Peninsula through Patagonia, Kilimanjaro, and the Himalayas to Greenland and the Arctic. Iconic glaciers—such as many in Glacier National Park, Montana—have already disappeared. Modeling efforts suggest that this is only the beginning; studies project that 52% of all small glaciers in Switzerland will disappear in the next 25 years (*2*), western Canada will lose 70 ± 10% of its total glacier volume by 2100 (*3*), and glacier mass losses in coming decades will be substantial for most parts of the Himalaya (*4*). Some glaciers are bucking the retreat trend, but these responses are com-

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A melting iceberg calved from Jakobshavn Glacier floats at the mouth of Disko Bay, Ilulissat, Greenland.

monly due to cyclical glacier-sediment interactions that are independent of climate (*5*) or are consistent with environmental changes resulting from climate change, such as increased precipitation (*6*).

Measurements of total glacier ice mass change are no less disturbing. Synthesizing results from several distinct methods for measuring ice mass provides conclusive evidence that the Greenland and West Antarctic Ice Sheets are shrinking at accelerating rates (*7*). The step change in Greenland ice loss likely began in the early 1990s (*8*); along the Antarctic Peninsula, signs of destabilization have marched south over the past one to two decades (*9*). Some of the most sobering observations, though, come from the Thwaites and Pine Island Glaciers region of West Antarctica.

Containing ~5 m of potential sea level rise, the West Antarctic Ice Sheet is particularly vulnerable because it rests on bedrock well below sea level and is exposed to warm ocean waters at depth. This setting is the key ingredient for triggering an amplifying loop of ice loss called the marine ice sheet instability, in which retreat, thinning, and speedup at the ice sheet edge produce runaway ice loss. Multiple studies indicate that this irreversible West Antarctic collapse is under way (*10*, *11*). The safety band of ice that protects more rapid ice loss around other parts of the Antarctic coast, especially in West Antarctica, is also showing signs of weakening (*12*).

SCIENTIFIC CHALLENGES

The risks and impacts of a 1- or 2-m sea level rise differ substantially for coastal cities and island nations. But perhaps even more important for planning is whether that flooding occurs in 2050 or 2150. This question can only be addressed by constraining the rates of ice loss, which must be a top research priority. Determining ice loss rates requires continued development of monitoring capacity, a sustained focus on process studies, and further integration of observations and modeling efforts.

Recognition of the value of glacier and ice sheet monitoring has increased in the past decade, but challenges remain. Limited satellite imaging has been a roadblock in assessing multidecadal ice-sheet–wide change. Much of what we know today came from glaciologists thoughtfully pulling data from satellites for which ice sheet monitoring was not a primary mission directive. The result has been data that are not consistently sampled across space or time, supporting important insights but falling short of providing a complete picture of global changes. Thankfully, ice research is becoming a greater priority. For example, the planned NASA–Indian Space Research Organisation (ISRO) Synthetic Aperture Radar (SAR) mission (NISAR) satellite will be the first radar satellite for which monitoring Earth's ice sheets is a primary mission directive. Securing funding support for long-term on-the-ground monitoring efforts, however, remains difficult.

Process studies, which are often more easily accommodated by commonly 3-year grant cycles, continue to be key to understanding the mechanisms that control glacier behavior. Efforts to determine the role of hydrology in ice motion (*13*) and understand glacier and ice-sheet surface-darkening (*14*) are examples of important and necessary research paths. Integration of observations and models is also crucial; an example is the increasing partnership between the Ice Sheet Model Intercomparison (currently ISMIP6) and Greenland Ice Sheet–Ocean Interactions (GRISO) projects. Better connections across observation and modeling research can improve model parameterizations, increase confidence in future forecasts, and pinpoint areas where additional in situ and remote sensing studies are needed.

Combining tools should also help with another challenge: determining methods and best practices to merge studies with disparate spatial and temporal scales. The next frontier in glaciology includes better integrating scales important for critical glacier processes (tens to hundreds of meters) with efforts to understand and predict ice-sheet–wide changes (hundreds to thousands of kilometers). Progress on this front will require substantial cross-disciplinary collaboration.

BEYOND SEA LEVEL RISE

Given the wide-ranging effects of glacier ice loss, it is imperative that glaciologists increase efforts to reach across disciplines, applying a systems science approach to elucidate how ice loss is both affected by and affects other elements of the hydrosphere, biosphere, anthroposphere, and beyond. Although sea level rise is the most common alarm bell from the glaciology community, the impacts of losing ice encompass much more, from reducing water security (*4*) to altering ecosystems (*15*). Glaciologists need to capture this breadth in research, data dissemination, and outreach efforts. Indeed, disseminating findings beyond the science community is an activity that must be encouraged, supported, and recognized by universities, research institutions, and funding agencies.

The evidence is overwhelming: Earth is losing its ice. Much of this loss is irreversible and the result of human-caused climate change (*1*). Unless substantial climate response action is taken and the trend of global temperature rise is reversed, we will continue to see Miami streets swallowed by the sea and glacier freshwater reservoirs melt into mud. And we can expect this pattern to continue for decades, centuries, and indeed, millennia. As scientists, we must make this reality clear and help to ensure that action is taken to minimize impacts globally. ■

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Saying goodbye to glaciers
Twila Moon (May 11, 2017)
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Editor's Summary

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and 10^{-1} s on the (100) facet. Therefore, the ability of the surfactant ligands to move on the surface allows the (111) facet to grow, whereas the low mobility of the ligands on the (100) facet blocks its growth. However, this mechanism is only for large facets. For small nanocrystals, the ligand molecules can easily fan out to make room for platinum atoms to land (*14*). Therefore, all facets grow when the nanocrystal is small. The critical size of about 5 nm may vary with temperature or the type of ligand. Our proposed ligand mobility–controlled selective facet–arrested shape evolution may apply to other ligands and nanoparticle shapes.

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SUPPLEMENTARY MATERIALS

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Movies S1 to S7

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GLACIERS

Attribution of global glacier mass loss to anthropogenic and natural causes

Ben Marzeion,[1]* J. Graham Cogley,[2] Kristin Richter,[1] David Parkes[1]

The ongoing global glacier retreat is affecting human societies by causing sea-level rise, changing seasonal water availability, and increasing geohazards. Melting glaciers are an icon of anthropogenic climate change. However, glacier response times are typically decades or longer, which implies that the present-day glacier retreat is a mixed response to past and current natural climate variability and current anthropogenic forcing. Here we show that only 25 ± 35% of the global glacier mass loss during the period from 1851 to 2010 is attributable to anthropogenic causes. Nevertheless, the anthropogenic signal is detectable with high confidence in glacier mass balance observations during 1991 to 2010, and the anthropogenic fraction of global glacier mass loss during that period has increased to 69 ± 24%.

Although glaciers store less than 1% of global ice mass (*1*), their mass loss has been a major cause of sea-level rise during the 20th century (*2*). Glaciers are important regulators of the seasonal water cycle, providing meltwater during dry seasons in many regions of the world (*3*, *4*). Glacier retreat often leads to the destabilization of mountain slopes and the formation of unstably dammed meltwater lakes, increasing the risk of rockslides and catastrophic outburst floods (*5*). The worldwide retreat of glaciers over the past decades has therefore had many impacts on human societies, which should increase over the 21st century because of continued mass losses (*6*–*8*).

Even though warming has accelerated over recent decades (*9*), glaciers have contributed to sea-level rise during most of the 20th century with relatively constant mass loss rates (*2*, *6*, *10*). The mass loss during the first decades of the 20th century was presumably governed by the loss of ice at low altitudes, when glaciers retreated from their 19th-century maxima at the end of the Little Ice Age (*11*). Because glacier extent responds to changes in the glacier mass balance (MB) with a lag of decades to centuries (*12*–*14*), glaciers provide an opportunity to directly perceive long-term climate change, unobscured by interannual variability. For this reason, images of retreating glaciers have become widely publicized illustrations of anthropogenic climate change. At the same time, the lagged response of glacier extents to climate changes complicates the attribution of the observed changes to any particular cause, because glacier mass change at any time is in part an ongoing adjustment of the glacier to previous climate change. The global retreat of glaciers observed today started around the middle of the 19th century, coinciding with the end of the Little Ice Age (*10*), when the anthropogenic forcing of the climate system was very weak as compared to today (*15*). Given the response times of glaciers, it is therefore reasonable to hypothesize that glaciers at present are responding both to naturally caused climate change of past centuries and to the anthropogenic warming that has become stronger in recent decades. There is evidence that the recent mass loss of individual glaciers exceeds values expected from internal variability (*16*), and a rough estimate has been made of the influence of anthropogenic warming on global glacier mass loss (*17*), but the explicit attribution of observed changes of individual glaciers is also complicated by the dynamic response of glaciers' geometries to climate forcing, because internal variability alone may cause glacier changes of the magnitude observed since the end of the Little Ice Age (*18*).

Here we quantify the evidence for a causal link between anthropogenic climate forcing and observed glacier surface MBs, not of individual glaciers but of all the world's glaciers outside of Antarctica combined. We then attribute the global glacier retreat since 1851 to natural and anthropogenic causes. We use a model of global glacier evolution that treats the MB of each of the world's glaciers contained in the Randolph Glacier Inventory (RGI) (*19*, *20*) individually, including a simple parametrization of ice dynamics leading to glacier hypsometry change (*6*). Forced by observed climate (*21*, *22*), the glacier model has been independently validated against both annual surface MB observations (fig. S1) and observed, temporally accumulated volume changes of hundreds of glaciers (*23*), and has been used to reconstruct and project the global glacier mass change from 1851 to 2300 (*6*), based on climate reconstructions and projections from the Coupled Model Intercomparison Project phase 5 (CMIP5). See the supplementary materials for a comprehensive description of the model.

For each of 12 reconstructions of the global climate between 1851 and 2010, produced by general circulation models (GCMs) from the CMIP5 ensemble (see table S1 for the list of the experiments used), we reconstructed the area and volume of each glacier in 1851 (*6*). From this

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reconstructed glacier state, we modeled the evolution of each glacier forward in time. This forward model was run twice for each GCM: once subject to all known forcings (i.e., solar variability, volcanic eruptions, land-use change, anthropogenic aerosols, and greenhouse gas emissions; we call these model runs the FULL runs below), and once subject to only natural forcings (i.e., solar variability and volcanic eruptions; we call these model runs the NAT runs below). Figure 1A shows the ensemble mean and standard deviation of the global mean specific MBs for the FULL and NAT runs. Because the global mean specific MB interpolated from observations (*23*) (we call these OBS below) is available as pentadal means only (black lines in Fig. 1A), we determined the pentadal means of the model runs (thick solid lines in Fig. 1A). In order to determine whether the modeled glacier MBs are consistent with observed MBs, we calculated the confidence level of the difference between modeled and observed MBs for each pentad. High confidence in this difference (i.e., red shading in Fig. 1B) thus indicates model results that are inconsistent with observations.

Modeled MBs in both the FULL and NAT runs are negative over essentially the entire period considered. However, a difference emerges over the course of the 20th century: Although the MB of the NAT runs becomes less negative as glaciers retreat to higher altitudes, thus stabilizing their MBs, there is a clear trend toward more negative MBs of glaciers in the FULL runs after 1965. Modeled MBs in the FULL runs are generally consistent with observations during the entire period covered by the latter, whereas the NAT runs are inconsistent with observations for at least the four pentads spanning 1991 to 2010 (Fig. 1B). This means that the anthropogenic signal is detectable in observed MBs over these four pentads with high confidence, unaffected by the result that MBs would have been negative during this period even without anthropogenic climate forcing. The anthropogenic fraction of global specific glacier mass loss rates increased from −6 ± 35% during the period 1851 to 1870 to 69 ± 24% during the period 1991 to 2010 (Fig. 1C, uncertainties correspond to one ensemble standard deviation). Without anthropogenic influence, glaciers would have contributed 99 ± 36 mm to global mean sea-level rise during 1851 to 2010. With anthropogenic influence, this number increases to 133 ± 30 mm (Fig. 1D, uncertainties correspond to one ensemble standard deviation).

When global mean MBs over longer periods than pentads are considered, it becomes evident that the NAT runs are inconsistent with observations for any period spanning 5 to 50 years and ending in 2010 (Fig. 2). The FULL runs are generally consistent with observations (Fig. 1B), but the simulated MBs are more negative than the observations during 2001 to 2010 (Fig. 1A), resulting in a difference between FULL runs and observations above the 85% confidence level for periods spanning 5 to 15 years and ending in 2010 (Fig. 2). This difference is caused by the FULL MBs for Svalbard and the Russian Arctic, which are too negative as compared to the observations.

Glacier mass losses attributable to human activity (shown as a fraction in Fig. 1C) have increased nearly steadily since 1860. In Fig. 3 we plot the year-by-year anthropogenic global mean specific mass balance $MB_{ANTH} = MB_{FULL} - MB_{NAT}$ against the concurrent anthropogenic radiative forcing R (*24*), and find a sensitivity dMB_{ANTH}/dR of −209 ± 33 kg year^{-1} W^{-1} (uncertainty corresponds to the 95% confidence interval). This is about twice as much as a direct calculation based on the latent heat of fusion of ice would give (−94 kg year^{-1} W^{-1}), indicating that feedbacks and the spatial distribution of anthropogenic climate change play an important role.

On the regional scale, the increased signal from internal climate variability, and greater uncertainty of GCM results (*25*), reduce the detectability of the anthropogenic signal. Although there are some regions where the anthropogenic signal is detectable (i.e., FULL runs are consistent with observations, whereas NAT runs are inconsistent), there are also a number of regions where the FULL runs are not consistent with observations (Fig. 2). The anthropogenic signal is detectable with high confidence in Alaska, western Canada and United States, Arctic Canada north and south, Greenland (only peripheral glaciers and not the ice sheet are considered there), north Asia, central Europe, low latitudes, and New Zealand (9 out of 18 regions), and with lesser confidence in Iceland, Scandinavia, and central Asia north (3 out of 18 regions). In Svalbard, the Russian Arctic, the Caucasus and Middle East, and the southern Andes, the FULL runs are inconsistent with observations (4 out of 18 regions), and in central Asia south and west both FULL and NAT runs are consistent with observations (2 out of 18 regions). A closer look at those regions where our method fails reveals that in the Caucasus and Middle East and the southern Andes, both the FULL and NAT runs underestimate the mass losses (in both cases, the FULL runs are closer to observations than the NAT runs).

In Svalbard and the Russian Arctic, the FULL run overestimates the mass loss, whereas the

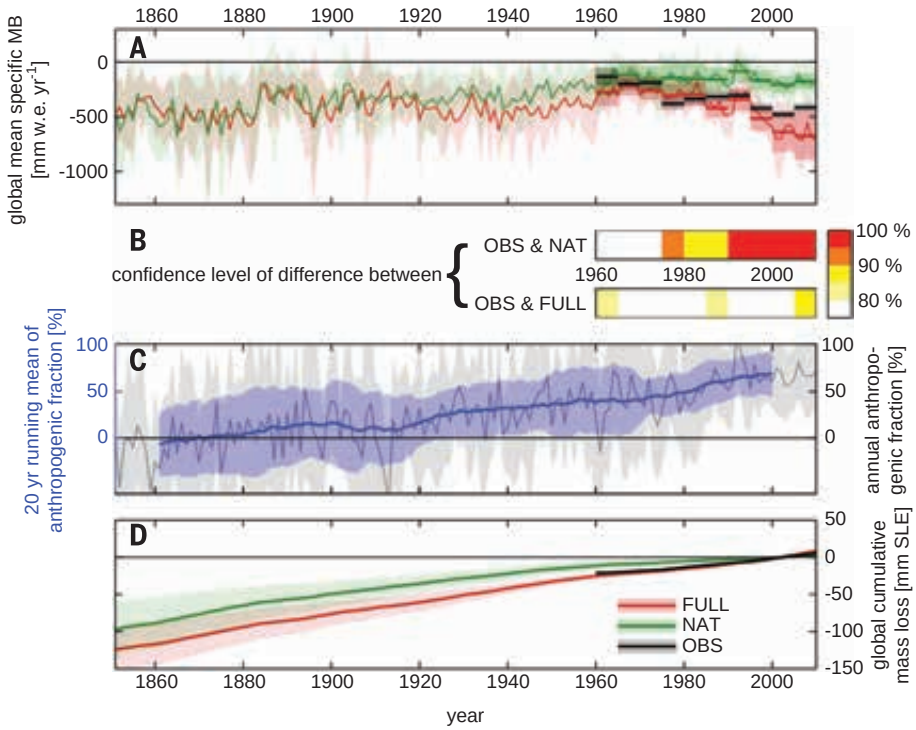

Fig. 1. Attribution of the anthropogenic signal in global mean glacier MBs. (**A**) Global mean specific MB time series (thin lines are the ensemble means, shading indicates one ensemble standard deviation) and pentadal means (thick lines are the ensemble means, shading indicates 1 SE; see the supplementary materials for the derivation of the error) are shown. Green, NAT results; red, FULL results; black, observations. (**B**) Confidence level of the difference between interpolated observations (OBS) updated from Cogley (2009) (*23*) and model results for the NAT and FULL models for each pentad. (**C**) Anthropogenic fraction of total glacier mass loss, annual values (gray), and running mean over 20-year periods (blue); the solid line is the ensemble mean; shading indicates one ensemble standard deviation. (**D**) Glacier contribution to global mean sea-level rise, relative to the mean of 1991 to 2010. Modeled results include modeled glacier area change; observations assume constant glacier area, as in the RGI (*19*) (the solid lines are the ensemble means; shading indicates one ensemble standard deviation).

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NAT run is consistent with observations (fig. S2). GCMs tend to have greater errors in this region than on global average (*25*), but they do not generally exhibit a stronger warming during summer months or reduced precipitation as compared to observations (*22*), which could explain too-negative modeled MBs. When we exclude calving glaciers from the observational data set (calving is not accounted for in the glacier model but does affect the observational estimate), the difference is reduced slightly, but not enough to lead to consistent results in these regions. Because validation of the glacier model on individual glaciers, as opposed to the regional mean, does not indicate a general underestimation of the modeled MBs in Svalbard (*6*), the reason for this regional inconsistency has to be related to the sampling of glacier MB observations (*26*), but ultimately remains unclear.

Because the glaciers are considerably out of balance with both modeled FULL and NAT climate at the beginning of the simulation period, it is not possible to distinguish between glacier mass losses caused by internal variability and natural forcing. In order to address this question, it would be necessary to identify the causes that led to the buildup of glacier mass during the Little Ice Age, a period not covered by the CMIP5 experiments. However, our results indicate that a considerable fraction of 20th-century glacier mass loss, and therefore also of observed sea-level rise, was independent of anthropogenic climate forcing. At the same time, we find unambiguous evidence of anthropogenic glacier mass loss in recent decades.

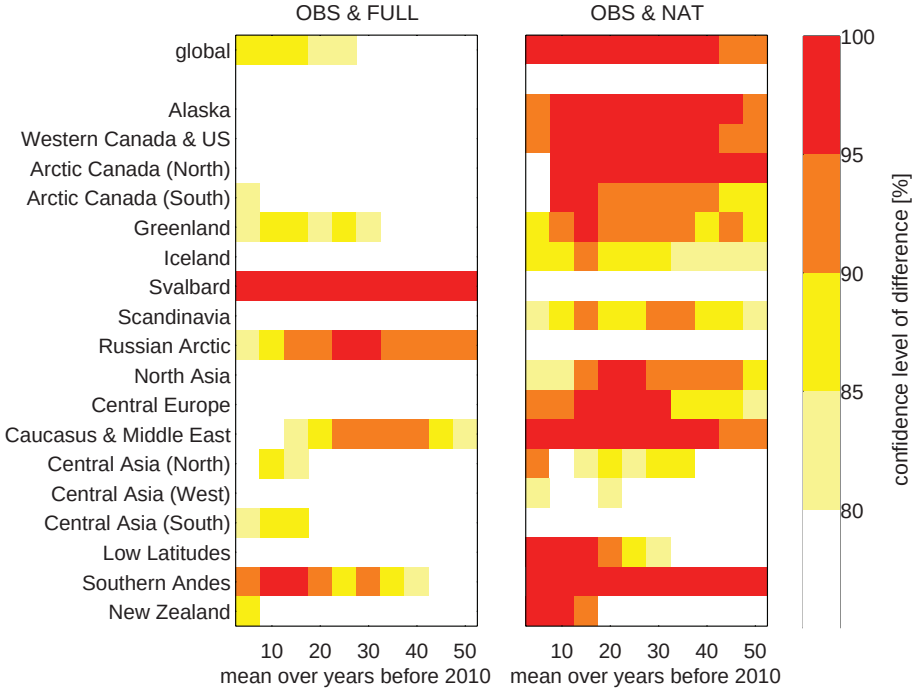

Fig. 2. Detection of the anthropogenic signal in global and regional glacier MBs over longer time intervals. Confidence levels of difference between observations (*23*) and model results for the NAT and FULL models for periods of different length ending in 2010 are shown. Regions are as defined in the RGI (*19*).

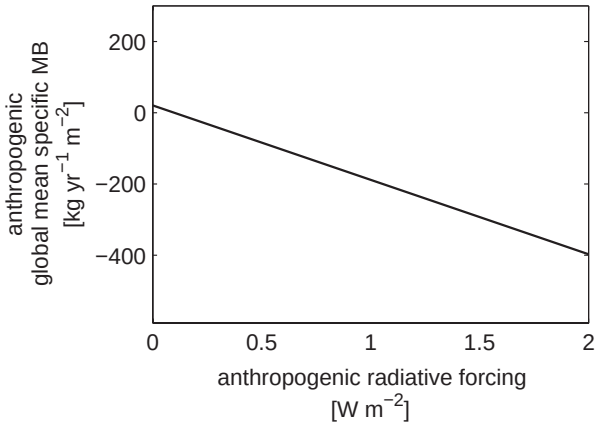

Fig. 3. Sensitivity of the instantaneous anthropogenic global mean specific MB to global mean anthropogenic radiative forcing. Annual values of MB_{ANTH} plotted against concurrent anthropogenic radiative forcing *R* (*24*) are shown. The Pearson correlation coefficient between the two is −0.71.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/345/6199/919/suppl/DC1
Methods
Figs. S1 and S2
Table S1
References (*27*–*33*)

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Attribution of global glacier mass loss to anthropogenic and natural causes
Ben Marzeion, J. Graham Cogley, Kristin Richter and David Parkes
(August 14, 2014)
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originally published online August 14, 2014

Editor's Summary

Putting the heat on Mother Nature

Humans are now the biggest cause of glacier melting. Until recently, that was not true. Glaciers take a long time––decades to centuries––to respond to the environmental changes that control their sizes. They have been retreating gradually from the peak levels they reached in the middle of the 19th century, at the end of a 500-year-long cold period called the Little Ice Age. Marzeion *et al.* show that that has recently changed though, as climate warming has continued: Over the past 20 or so years, the anthropogenic contribution to glacial mass loss has increased markedly (see the Perspective by Marshall).

Science, this issue p. 919; see also p. 872

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nature geoscience

ARTICLES

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Centennial glacier retreat as categorical evidence of regional climate change

Gerard H. Roe[1]*, Marcia B. Baker[1] and Florian Herla[2]

The near-global retreat of glaciers over the last century provides some of the most iconic imagery for communicating the reality of anthropogenic climate change to the public. Surprisingly, however, there has not been a quantitative foundation for attributing the retreats to climate change, except in the global aggregate. This gap, between public perception and scientific basis, is due to uncertainties in numerical modelling, and the short length of glacier mass-balance records. Here we present a method for assessing individual glacier change based on the signal-to-noise ratio, a robust metric that is insensitive to uncertainties in glacier dynamics. Using only meteorological and glacier observations, and the characteristic decadal response time of glaciers, we demonstrate that observed retreats of individual glaciers represent some of the highest signal-to-noise ratios of climate change yet documented. Therefore, in many places, the centennial-scale retreat of the local glaciers does indeed constitute categorical evidence of climate change.

Alpine glaciers are consequential and captivating elements of the Earth system that feature prominently in the lives of nearby communities[1]. The nature of glacier motion was a research challenge for nineteenth-century physicists[2,3], and the late Holocene history of glacier margins has been a primary target of modern palaeoclimate science[4]. Consequently, the century-scale length history of several hundred glaciers is well known (for example, Fig. 1)[4,5]. Whilst glacier mass balance (that is, area-averaged accumulation minus ablation, $\equiv b$ (m yr^{-1})) is a more direct measure of climate[6,7] than glacier length, only a few dozen mass-balance records extend for more than two decades.

The century-scale, near-global retreat of glacier fronts seems improbable without some coordinating global climate change. However, the formal statistical assessment of the role of climate change in glacier retreat has been limited to the numerical modelling of three individual glaciers, each with only a single set of model parameters[8]; and to a comparison of the global aggregate glacier mass loss in forced and unforced integrations of global climate models[9].

By itself, any single glacier is a blunt statistical instrument. Each is a unique product of its local climate and landscape. Characteristic glacier-length response times of several decades[10] imply only a few independent degrees of freedom in a centennial record, resulting in poor statistical resolving power to evaluate a trend. In part because of these factors, the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) concluded only it was 'likely' that a 'substantial' part of glacier retreat is due to anthropogenic climate change, a much weaker attribution than for other metrics of climate change[11]. Here we introduce a method to combine glacier observations with the better-resolved local meteorological trends, which facilitates strong conclusions. The centennial-scale retreats of 37 widely dispersed glaciers have each necessarily required a climate change. And while the cause cannot be attributed purely from observations, the required climate changes are centennial-scale trends that are globally distributed.

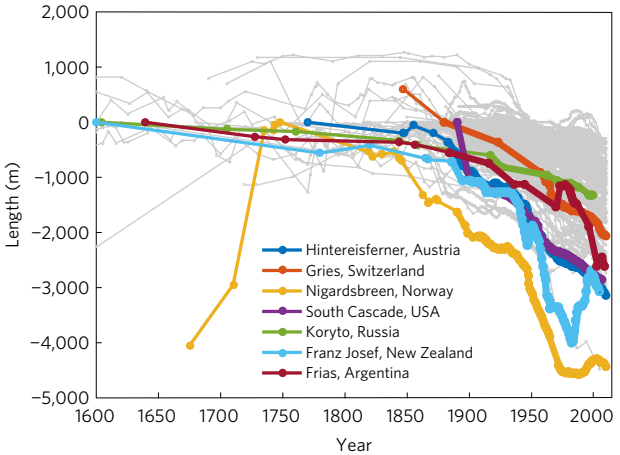

Figure 1. The global record of glacier lengths[5], for 158 glaciers with 20 or more individual observations (shown as dots). Coloured lines show the specific glaciers analysed in Fig. 4.

The signal-to-noise ratio as a metric of glacier change

We relate s_L, the signal-to-noise ratio of glacier length ($\equiv L$), to s_b, the signal-to-noise ratio of mass balance ($\equiv b$). Let ΔL be the change in length over some period of time, and let σ_L be the standard deviation in the absence of any climate trend. Then $s_L \equiv \Delta L/\sigma_L$. Likewise, $s_b \equiv \Delta b/\sigma_b$. We first establish that s_L is straightforwardly related to s_b, and that the relationship is insensitive to uncertainties in glacier parameters. The result is robust and depends only on the fundamental property that glaciers integrate mass balance on timescales of a few decades.

In a refinement of earlier models[12,13], previous work has shown that glacier flow on a sloping bed can be accurately emulated by a linear, third-order differential equation (Methods)[14]. Let $\Delta b(t_o)$ be the change in mass balance due to a linear trend applied over a

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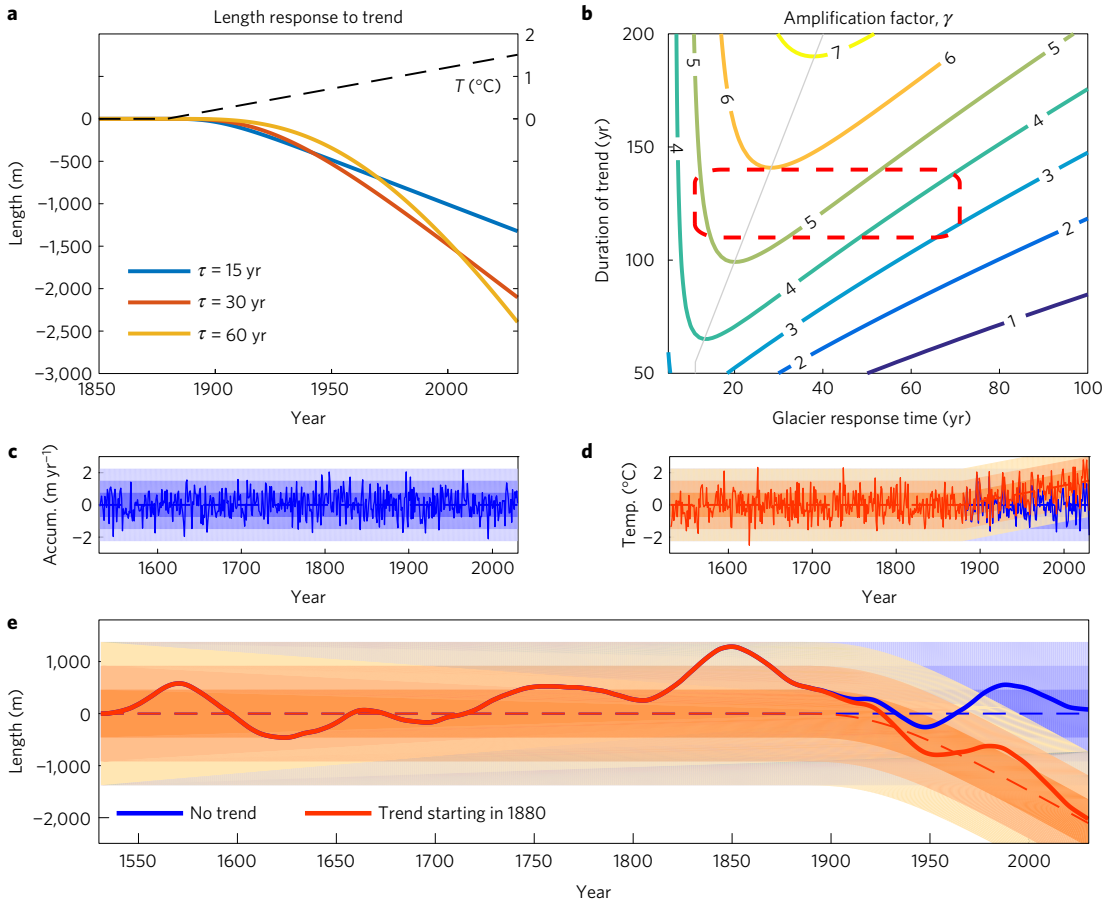

Figure 2. The response of idealized glaciers to climate. **a**, The response to a warming trend (dashed line, right axis) of three idealized glaciers with response times of $\tau = 15$, 30 and 60 yr (coloured lines, left axis). **b**, The amplification factor $\gamma(\tau, t_o)$, in the relationship $s_L = \gamma \cdot s_b$. The dashed red box covers the approximate range applicable to alpine glaciers. Thus, $\gamma \simeq 4$ to 6 for a wide range of the relevant parameter space. **c**, A 500-yr segment of synthetic, random white-noise accumulation ($\sigma_P = 0.75$ m yr^{-1}), shading denotes 1, 2 and 3σ ranges. **d**, As for **c**, but for melt-season temperature ($\sigma_T = 0.75$ °C), and with an imposed 1 °C-per-century warming trend beginning in 1880. The blue line and shading have no warming trend. **e**, Response of a glacier with $\tau = 30$ yr, $\beta = 180$. Due to the applied warming trend from 1880 to 2010, $\Delta L = -1{,}700$ m, $\sigma_L = 460$ m, giving $s_L = -3.7$. In these simulations, anomalies in temperature and mass balance are related via $b' = -\mu T'$, with $\mu = 0.65$ m yr^{-1} °C^{-1}.

period t_o. Our model yields $\Delta L(t_o) = \phi(t_o, \tau) \cdot \beta \cdot \Delta b(t_o)$, where τ and β are functions of glacier geometry. The glacier response time $\tau = -H/b_t$, where H is a characteristic ice thickness and b_t is the (negative) mass balance at the terminus[12]; β is the ratio of the glacier area to the product of H and the width across the terminus. The function $\phi(t_o, \tau)$ embodies the ice dynamics, and captures three distinct stages of adjustment: changes in interior ice thickness drive changes in ice flux at the terminus that, in turn, drive changes in glacier length[12,14]. τ is central to a glacier's response: Fig. 2a shows $\Delta L(t)$ for a warming trend of 1 °C per century, for three glaciers with different τ (and fixed β). Physically, τ controls how quickly a glacier responds to climate variations and also how strongly the glacier is restored to equilibrium[12–14]: small-τ glaciers respond quickly but are less sensitive, whereas large-τ glaciers respond slowly but are ultimately more sensitive. These fundamental trade-offs are independent of the model used (see Supplementary Information), and mean that a century or so after a climate trend commences, the amount of retreat is relatively insensitive to several-fold variations in τ (Fig. 2a).

Our model, and all equivalent models, also yield $\sigma_L \propto \beta \cdot \sigma_b$ (Methods). Thus, s_L can be written as:

$$s_L = \gamma(t_o, \tau) \cdot s_b \qquad (1)$$

$\gamma(t_o, \tau)$ is an amplification factor that depends only on the duration of the trend and the glacier response time. The counteracting tendencies of initial responsiveness versus long-term sensitivity mean that $\gamma(t_o, \tau)$ is quite insensitive to τ. For example, for a 130-yr trend, glacier length is a fourfold to sixfold amplifier of the mass-balance signal-to-noise ratio, across a wide range of response times (Fig. 2b). The relative constancy of γ is key to estimating s_L from meteorological observations. Note both ΔL and σ_L are proportional to the parameter β and so it drops out of s_L.

The relationship between s_L and s_b can be illustrated with a synthetic example for typical climate trends and variability. Assume a 1 °C-per-century increase in melt-season (June–September) temperature ($\equiv T$) beginning in 1880, no trend in annual-mean precipitation ($\equiv P$), and white-noise interannual variability (consistent with observations[7]) characterized by $\sigma_T = 0.75$ °C and $\sigma_P = 0.75$ m yr^{-1}, respectively (Fig. 2c,d). A simple mass-balance model is $b' = P' - \mu T'$, where μ is a melt factor ($= 0.65$ m yr^{-1} K^{-1})[15], and primes denote fluctuations about the long-term mean. After 130 yr of the imposed trend, $s_b = -0.65$. For $\tau = 30$ yr and $\beta = 180$, we get $\Delta L = -1{,}700$ m and $\sigma_L = 460$ m (Fig. 2e). Thus, the retreat is approximately three-and-a-half standard deviations ($s_L = \Delta L/\sigma_L \simeq -3.5$), consistent with an amplification factor of $\gamma \simeq 5.7$ (equation (1) and Fig. 2b).

An application to Hintereisferner, Austria

We next present the steps of our analysis for Hintereisferner in the Austrian Alps (Fig. 1). Applying least-squares regression for the

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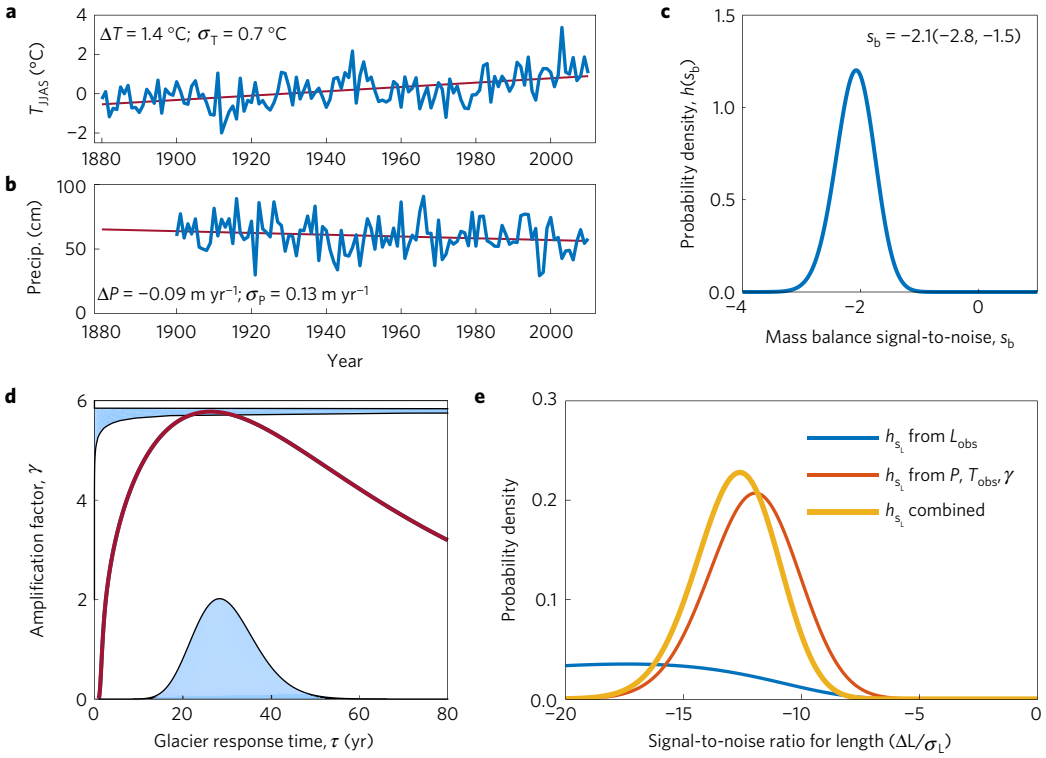

Figure 3 | Analysis for Hintereisferner (Austrian Alps, 46.8° N, 10.8° E). **a**, Melt-season (June–September) temperature from the Berkeley Earth data set of gridded station observations[17]. The best-fit trend, the change since 1880 and the standard deviation are also shown. **b**, As for **a**, but from the Legates and Willmot data set of gridded annual-mean precipitation[18], with the trend extrapolated to 1880. **c**, The PDF of the signal-to-noise ratio for mass balance, s_b (equation (2)), with median and 95% bounds also given. **d**, The blue shading on the *x* axis shows the PDF of uncertainty in glacier response time, τ; the red curve shows the relationship between τ and the amplification factor, γ, for a 130-yr trend; the blue shading on the *y* axis shows the PDF for γ that results from the PDF for τ being projected onto the y axis via the red line. **e**, PDFs of length signal-to-noise ratio, s_L, from different methods: blue, s_L from observations of *L*; red, s_L from *T*, *P* observations and the amplification factor γ (that is, equation (1)); orange, combined PDF using Bayes' theorem.

period 1880–2010, the glacier retreated 2,800 m with a standard deviation of 130 m about that trend. However, there are only three effective degrees of freedom in the record (Methods), so neither ΔL nor σ_L is well constrained. Consequently, the probability density function (PDF) of their ratio ($\equiv h_{s_L}|^{L_{obs}}$) is very broad (Fig. 3e and Methods): while it is extremely unlikely (<1%) that $s_L > 0$, one cannot rule out the possibility its magnitude is very large (that is, $s_L < -20$). In other words, there is not much information about s_L from the glacier length alone.

An independent approach to calculating s_L uses equation (1). To that end, we build a simple mass-balance model using long-duration, gridded instrumental observations[16,17] of *T* and *P*, scaled by the observed variability of the much shorter winter (b_w) and summer (b_s) mass-balance records[7,18]:

$$b'(t) = b'_w(t) + b'_s(t) = \sigma_{b_w}\frac{P'(t)}{\sigma_P} + \sigma_{b_s}\frac{T'(t)}{\sigma_T} \qquad (2)$$

where $\sigma_{(x)}$ is the standard deviation of *x*. Thus, the modelled mass balance matches the observed variance, and combines the observed signal-to-noise ratios of *P* and *T*. Normalizing by σ_P accounts for orographic-precipitation effects since fractional variations in precipitation are relatively uniform in mountainous areas. Between 1880 and 2010, Hintereisferner experienced strong warming: $\Delta T = +1.4\,°C$, with $\sigma_T = 0.7\,°C$ (Fig. 3a); and some drying: $\Delta P = -0.09\,m\,yr^{-1}$, with $\sigma_P = 0.13\,m\,yr^{-1}$ (Fig. 3b, extrapolated from a 100-yr record). Observations from the adjacent Vernagtferner[18] give $\sigma_{b_w} = 0.22\,m\,yr^{-1}$, $\sigma_{b_s} = 0.42\,m\,yr^{-1}$. Thus, from equation (2), the median (and 95% bounds) for $s_b = -2.1(-2.8, -1.5)$ (Fig. 3c and Methods): s_b is negative but with some uncertainty. Although the detrended $b'(t)$ is consistent with white noise, we evaluate the potential impact of climatic persistence in the Supplementary Information.

For Hintereisferner[19], $H \simeq 170\,m$ and $b_t \simeq -6\,m\,yr^{-1}$, giving $\tau \simeq 30$ yr. Formulae for τ vary in the literature[12,13], so we allow broad uncertainty; we represent its PDF by a gamma distribution with $\sigma_\tau = \tau/4$. Figure 3d shows this nonetheless results in a very narrow PDF of γ, centred on $\gamma \simeq 5.6$. Hintereisferner thus acts as a near-optimal amplifier of the climate signal-to-noise ratio. From equation (1) the PDFs of γ and s_b can be combined to give a second PDF for s_L ($\equiv h_{s_L}|^{T,P_{obs}}$), based only on instrumental observations and the approximately several-decade response time of this glacier (Fig. 3e). This PDF rules out extremely negative s_L (for example, $s_L \leq -20$) as inconsistent with observed climate trends (that is, $s_b \simeq -2$) and the roughly sixfold amplification by the glacier length.

These two PDFs of s_L, one based on observations of *L*, and one based on γ and s_b, are independent. Therefore, they can be combined using Bayes' theorem (Methods)[20]. The resulting median (and 95% bounds) is $s_L = -13(-17, -10)$ (Fig. 3e). This is an extraordinarily large magnitude compared with other documented climate metrics. For comparison, the local ΔT near Hintereisferner is 2σ, and the global-mean, annual-mean ΔT trend over the same period is 6σ.

The result that $\Delta L \approx -13\sigma_L$ must not itself be directly equated to statistical significance because length variations are correlated in time. To proceed, we solve for the PDF of σ_L from the relation $\sigma_L = \Delta L|^{obs}/s_L$, using the known observed retreat and the combined PDF for s_L. For Hintereisferner, we find σ_L (and 95% bounds) = 220(170, 280) m. Although this estimate depends primarily on observations, it is consistent with calculations from modelling

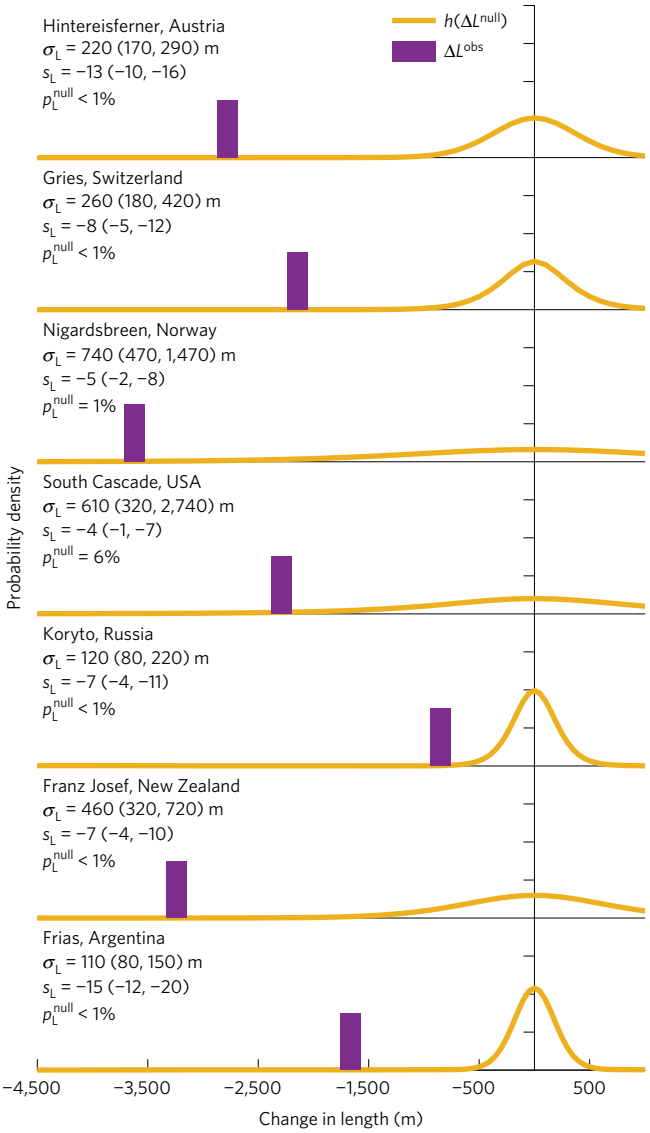

Figure 4 | Analysis of glacier retreat from around the world (see Fig. 1). For each glacier, the PDF for ΔL in any 130-yr period with no climate change is shown, and compared with the observed retreat represented by the vertical bar. Also given is the estimated standard deviation and signal-to-noise ratio (with 95% bounds), and the p value for the null hypothesis—the likelihood that the observed retreat occurred in the absence of a climate change. All PDFs have areas normalized to 1. See Supplementary Information for 30 other glaciers worldwide, and a full table of the analyses.

(Methods). Finally, we test against a null hypothesis of no climate change. Using equation (1), the probability distribution of a given ΔL occurring in any 130-yr period without climate change comes from combining the PDFs for each of the terms on the right-hand side of: $\Delta L|^{null} = \sigma_L \cdot \gamma \cdot s_b|^{null}$, where the PDF for $s_b|^{null}$ comes from the detrended mass-balance observations (Methods). We find the probability that the observed retreat comes from the null distribution is minuscule ($p_L^{null} = 0.001\%$, Fig. 4a); it is thus highly significant and must be attributed to a climate change. In general, the statistical significance of the glacier retreat may be larger or smaller than that of other local climate metrics. For example, although the global aggregate of the much shorter duration glacier mass-balance observations is negative and significant at the 5% level[7], only 17/48 and 4/48 of the individual summer and winter mass-balance records longer than 10 years exhibit significant trends (all negative)[7]. For Hintereisferner, s_L and the statistical significance are so large because of the observed drying in addition to the observed warming (Fig. 3a,b), and because the Bayesian step combining PDFs with length observations indicates a slightly more negative s_L (Fig. 3e).

An evaluation of glaciers worldwide

The foregoing analysis can be applied to any glacier with a long length record and known mass-balance variability. The results for seven widely distributed glaciers (Fig. 1) are shown in Fig. 4. Although the size of the retreats vary by more than a factor of five, for each glacier it is very unlikely that it could have occurred without climate forcing. The least significant retreat, $p_L^{null} = 6\%$, is South Cascade Glacier, which has a small median $s_b \simeq -0.7$, resulting from a relatively small warming in a maritime climate where winter mass-balance variability exceeds that in summer[7] (Supplementary Information).

We have analysed a total of 37 glaciers worldwide, selecting those with the longest mass-balance and length records. All steps and results are detailed in the Methods and Supplementary Information. In several cases, nearby mass-balance records were used, and when length observations were too sparse to characterize the degrees of freedom, a uniform negative-definite $h_{s_L}|^{L_{obs}}$ was assumed, consistent with the observed retreat (that is, $\Delta L < 0$) of all evaluated glaciers (Fig. 1 and Supplementary Information), and the fact that σ_L is positive. For the 37 glaciers, the median values of s_L and σ_L range from −2 to −15 and from 120 m to 750 m, respectively. Our analyses represent an approximately tenfold increase in the number of glaciers for which σ_L has been estimated; three of our selected glaciers have previous model-based estimates of σ_L that lie within our observation-based ranges[8,14]. Such estimates are valuable for putting reconstructions of past Holocene glacier fluctuations into context[15]. We note that the response of glacier length to climate trends and to natural variability form complementary pairs: glaciers that are sensitive to climate change also tend to have higher variability.

For 21 of the 37 glaciers, $p_L^{null} \leq 1\%$. Adopting IPCC nomenclature, it is thus 'virtually certain' that the retreat of each of these individual glaciers required a climate change. A further seven have $p_L^{null} \leq 5\%$. The least significant, Rabots Glacier in northern Sweden, has $p_L^{null} = 11\%$. Thus, for all but one glacier, it is 'very likely' (≥90%, IPCC) their retreat is attributable to climate change.

These calculations and uncertainty estimates can undoubtedly be refined and improved by more sophisticated mass-balance models and by detailed numerical case studies with explicit valley geometry, and of course our analyses do not, on their own, speak to the cause of the required climate change. However, the decadal response time of glaciers means their centennial retreat is predominantly a response to the twentieth-century climate trends rather than being a dynamical recovery from any antecedent conditions, such as the putative Little Ice Age[21]. The fundamental principle evinced here—that glaciers act as several-fold amplifiers of the signal-to-noise ratio of local climate trends—is robust. The principle is not limited to glaciers. Any component of the climate system with a decadal timescale will damp high-frequency variations and integrate centennial-scale trends. However, glaciers are perhaps unique in combining a decadal timescale with a strong sensitivity and simple dynamical response to temperature, creating near-maximum signal-to-noise ratios for centennial-scale climate change (Fig. 2b). In combination with climate and glacier observations, this has enabled our quantification of just how far individual glaciers have been driven from their pre-industrial states by climate change.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

G.H.R., M.B.B. and F.H. planned the analyses, which G.H.R. performed. All authors contributed to the interpretation of the results and to writing the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.H.R.

Competing financial interests

The authors declare no competing financial interests.

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Methods

A three-stage model. A refinement of earlier analytical glacier models[12,13] was developed in ref. 14, and showed that numerical models of ice flow on a constant slope could be accurately emulated by a third-order linear differential equation:

$$\left(\frac{\mathrm{d}}{\mathrm{d}t}+\frac{1}{\epsilon\tau}\right)^3 L' = \frac{\beta}{\epsilon^3\tau^2}b'(t) \tag{3}$$

where $L'(t)$ is the length perturbation from some long-term, mean-state position, driven by mass-balance fluctuations, $b'(t)$. $\tau=-H/b_t$, where H is a characteristic thickness and b_t is the (negative) mass balance at the terminus; $\beta=A_{tot}/(wH)$, where A_{tot} is the mean-state glacier area and w is the characteristic width at the terminus; and $\epsilon=1/\sqrt{3}$. Reference 14 showed that equation (3) captures three essential stages of glacier adjustment: changes in interior ice thickness drive changes in ice flux at the terminus that, in turn, drive changes in glacier length. Equation (3) has analytic solutions that facilitate efficient analyses over a wide range of parameter space.

Response to a trend. Consider a linear trend in mass balance commencing at $t=0$. Let $\Delta b(t_o)$ be the resulting change in mass balance after a time t_o has elapsed. The exact solution of equation (3) for the resulting length change, $\Delta L(t_o)$, is:

$$\Delta L(t_o)=\phi(t_o,\tau)\cdot\beta\cdot\Delta b(t_o) \tag{4}$$

where

$$\phi(t_o,\tau)=\tau\left[\frac{3}{r}(\mathrm{e}^{-r}-1)+1+\mathrm{e}^{-r}\left(\frac{r}{2}+2\right)\right] \tag{5}$$

and $r=t_o/\epsilon\tau$. We note that $\phi(t_o,\tau)\rightarrow\frac{\tau}{t_o}(t_o-3\epsilon\tau)$ in the limit that $t_0\gg\epsilon\tau$. Equation (4) is used to calculate the curves in Fig. 2a.

Glacier-length variance. Consider stochastic white-noise interannual fluctuations in mass balance (that is, random, year-to-year variability due to the vagaries of the weather, with no year-to-year persistence). Let the standard deviation of such fluctuations be σ_b. Such mass-balance fluctuations drive variability in glacier length, characterized by a standard deviation σ_L. Ref. 14 shows that:

$$\sigma_L=\beta\cdot\psi(\tau)\cdot\sigma_b \tag{6}$$

where

$$\psi(\tau)=\tau\left\{\frac{(1-\kappa)(1+4\kappa^2+\kappa^4)}{(1+\kappa)^5}\right\}^{\frac{1}{2}} \tag{7}$$

with $\kappa=1-(\Delta t/\epsilon\tau)$ and $\Delta t=1$ yr. We note that $\psi(\tau)\rightarrow(3\tau\Delta t/16\epsilon)^{1/2}$ in the limit of $\epsilon\tau\gg\Delta t$.

Estimated variance for Hintereisferner. Taking Hintereisferner in the Austrian Alps as an example, reasonable values for parameters are[19]: $A_{tot}\simeq10.5\,\mathrm{km}^2$, $w\simeq400$ m, $H\simeq170$ m; $b_t\simeq-6.5\,\mathrm{m\,yr^{-1}}$, giving $\beta\simeq150$ and $\tau\simeq30$ yr. With $\sigma_b\simeq0.5\,\mathrm{m\,yr^{-1}}$ from the adjacent Vernagtferner[7,18], equation (6) yields $\sigma_L\simeq230$ m. This value is close to the central estimate of σ_L made from observed retreat of Hintereisferner and local climate trends: $\sigma_L\simeq220$ m (Fig. 4).

Signal-to-noise ratio, s_L. Therefore, for a climate trend superposed on natural interannual variability, the signal-to-noise ratio for glacier length, s_L, can be formed from equation (4) divided by equation (6):

$$s_L=\frac{\Delta L}{\sigma_L}=\frac{\phi(t_o,\tau)}{\psi(\tau)}\cdot\frac{\Delta b(t_o)}{\sigma_b}=\gamma(t_o,\tau)\cdot s_b \tag{8}$$

Contours of $\gamma(t_o,\tau)$ are plotted in Fig. 2b.

Signal-to-noise ratio from length observations. We considered glacier records from a compilation of 471 glacier-length histories worldwide[5]. The data set uses Stineman interpolation in between individual length observations to produce annual time series, although our results are not sensitive to the interpolation method. We selected 37 glaciers in total (in each of five regions—see Supplementary Information), and focus on the period 1880 to 2010. The main criteria in selecting glaciers were long mass-balance records and a broad geographic distribution. However, we also preferentially selected glaciers with near-continuous length observations, although for some regions such as Asia and South America, this criterion could not always be met.

The signal-to-noise ratio is given by $s_L=\Delta L/\sigma_L$, where ΔL is the change in length and σ_L is the standard deviation of the variability about that trend. We estimate s_L from least-squares linear regression. Let $h_{s_L}(s_L)|^{L_{obs}}$ be the probability density function (PDF) of s_L, and let $\overline{\Delta L}$ and $\overline{\sigma_L}$ be the central estimates of ΔL and σ_L, respectively. From ref. 22, and the standard formulae for uncertainties in regression parameters[23] applied to glacier trends[24], it can be shown that:

$$h_{s_L}(s_L)|^{L_{obs}}=\sqrt{\frac{\nu-1}{12}}\,\mathcal{F}\left(\sqrt{\frac{\nu-1}{12}}s_L,\nu-1,\frac{\overline{\Delta L}}{\overline{\sigma_L}}\sqrt{\frac{\nu-1}{12}}\right) \tag{9}$$

where $\mathcal{F}(x,\nu-1,\mu)$ is a non-central t-distribution of the variable x with $\nu-1$ degrees of freedom, and non-centrality parameter μ (refs 22,24). The formula in equation (9) was verified in Monte Carlo simulations of time series with stipulated trends added to random realizations of noise.

Degrees of freedom in a record. We estimate the number of degrees of freedom, ν, in the glacier record following a procedure recommended in ref. 23. We fit a third-order autoregressive process to the length data[14,23,25] and calculate the associated autocorrelation function, $r(\tau)$. The effective degrees of freedom are then given by:

$$\nu=\frac{n\Delta t}{\Delta t+2\int_0^\infty r(\tau)\mathrm{d}\tau} \tag{10}$$

where n is the number of years in the record and $\Delta t=1$ yr. The number of degrees of freedom in the length observations ranges from <1 up to ~6. Low degrees of freedom yield broad distributions for $h_{s_L}|^{L_{obs}}$ (for example, Fig. 3e), so that the most important information from the length observations is only that s_L is not positive. When this method identifies $\nu\leq1$, or when the length records are sparse, $h_{s_L}|^{L_{obs}}$ cannot be calculated in this way. We instead stipulate a uniform negative-definite $h_{s_L}|^{L_{obs}}$, consistent with the observed retreat (that is, $\Delta L<0$) of all glaciers analysed and the fact that σ_L is positive definite (see also Supplementary Information). Our second method for calculating s_L (described below) uses climate observations with many more degrees of freedom, which produces a much narrower PDF (for example, Fig. 3e). When the two PDFs are combined, the narrower PDF dominates (Fig. 3e), and so our results and conclusions are not sensitive to the estimate of ν.

Signal-to-noise ratio from climate observations and glacier amplification factor. The second method for calculating s_L is to use the relationship from equation (8):

$$s_L=\gamma(t_o,\tau)\cdot s_b \tag{11}$$

Calculating s_b and its persistence. As described in the main text, the mass-balance model is:

$$b'(t)=b'_w(t)+b'_s(t)=\sigma_{b_w}\frac{P'(t)}{\sigma_P}+\sigma_{b_s}\frac{T'(t)}{\sigma_T} \tag{12}$$

Values of P' (annual mean) come from the Legates and Willmot data set[17]. Values of T' (June to September in the Northern Hemisphere extratropics, December to March in Southern Hemisphere extratropics; annual mean in the tropics) come from the Berkeley Earth data set[16]. The data were taken from the nearest land grid point to each glacier's location. The data sets were chosen for their high spatial resolution, but alternative data sets show similar trends.

The PDF of s_b ($\equiv h_{s_b}$) is calculated using the same non-central t-distribution as equation (9):

$$h_{s_b}(s_b)|^{T,P_{obs}}=\sqrt{\frac{\nu-1}{12}}\,\mathcal{F}\left(\sqrt{\frac{\nu-1}{12}}s_L,\nu-1,\frac{\overline{\Delta b}}{\overline{\sigma_b}}\sqrt{\frac{\nu-1}{12}}\right) \tag{13}$$

Here, the degrees of freedom are also calculated by fitting an autoregressive model to $b'(t)$. Only 3 out of the 37 glaciers analysed have a mass-balance time series that indicates any persistence (documented in the Supplementary Spreadsheet), with most being well characterized by white noise, consistent with mass-balance observations[7,26]. Thus, for almost all of the records, the degrees of freedom are equal to the number of years in the record. The majority of the mass-balance trends are dominated by trends in summer mass balance due to the melt-season temperature trends, which is also seen in the much shorter records of actual glacier mass balance[7].

Calculating the PDF of γ from the PDF of τ. The central estimate of τ comes from the relationship $\tau=-H/b_t$. For each glacier, the source references for the characteristic thickness H and terminus ablation rate b_t are given in the Supplementary Spreadsheet. For the PDF of uncertainty in τ ($\equiv h_\tau(\tau)$) we take a gamma distribution (ensuring τ is positive definite), with a standard deviation of $\tau/4$ (Fig. 3d). Thus, the 95% uncertainty bounds on τ (that is, $\pm2\sigma$) are equal to τ itself—a broad and thus conservative estimate of the uncertainty.

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The PDF of $\gamma(t_o,\tau)$ ($\equiv h_\gamma$) comes from equation (8), and applying the relationship:

$$h_\gamma(\gamma)=\frac{h_\tau(\tau)}{\partial\gamma/\partial\tau} \tag{14}$$

For our analyses $t_o=130$ yr (1880 to 2010). The nature of γ is such that even very broad PDFs in τ map onto narrow PDFs of γ (Fig. 3d).

The PDF of s_L. Finally, the PDF of s_L ($\equiv h_{s_L}(s_L)|^{T,P_{obs}}$) comes from combining h_γ and h_{s_b}. The probability that s_L lies between any given value s_L and s_L+ds_L is given by:

$$h_{s_L}(s_L)\mathrm{d}s_L=\sum h_\gamma(\gamma)\mathrm{d}\gamma\cdot h_{s_b}(s_b)\mathrm{d}s_b \tag{15}$$

where the sum is taken over all possible pairs (s_b, γ) for which $s_b\cdot\gamma=s_L$. Using $\mathrm{d}s_b/\mathrm{d}s_L=1/\gamma$, and taking the limits that $\mathrm{d}s_L,\mathrm{d}\gamma,\mathrm{d}s_b\to 0$, the sum becomes an integral:

$$h_{s_L}(s_L)|^{T,P_{obs}}=\int_0^\infty h_\gamma(\gamma)\cdot h_{s_b}(s_L/\gamma)\cdot\frac{1}{\gamma}\cdot\mathrm{d}\gamma \tag{16}$$

In other analyses in this study, the PDFs for all variables that are the product or ratio of two other variables are generated in a similar fashion. Where noted, the PDFs generated in this way have been verified with Monte Carlo simulations.

Combining the PDFs for s_L using Bayes' theorem. $h_{s_L}|^{L_{obs}}$ and $h_{s_L}|^{T,P_{obs}}$ are independent and so can be combined using Bayes' theorem to yield an updated, posterior PDF for s_L. We regard $h_{s_L}|^{L_{obs}}$ as the prior PDF that is updated by new information from the observed s_b. $h_{s_L}|^{T,P_{obs}}$ is equivalent to the likelihood function $\mathcal{L}(s_L|s_b)$, the likelihood of s_L given the new information s_b (ref. 20). For glaciers whose length history is too sparse (meaning if there are temporal gaps in the observations that are comparable to τ) or if the degrees of freedom are less than one, we stipulate an uninformative, flat prior for $h_{s_L}|^{L_{obs}}$ that is negative definite: $h_{s_L}=$ constant for $s_L<0$, and $h_{s_L}=0$ otherwise. This is consistent with the observed negative ΔL of all glaciers analysed and the fact that σ_L is positive definite (see also Supplementary Information). Then the posterior PDF for s_L is given by:

$$h_{s_L}(s_L)|^{post}=k\cdot h_{s_L}(s_L)|^{L_{obs}}\cdot h_{s_L}(s_L)|^{T,P_{obs}} \tag{17}$$

where k is a normalization constant independent of s_L. An example of $h_{s_L}(s_L)|^{post}$ for Hintereisferner is shown in Fig. 3e.

Estimating σ_L from s_L. We estimate the PDF of σ_L ($\equiv h_{\sigma_L}$) from the relationship:

$$\sigma_L=\frac{\overline{\Delta L}}{s_L} \tag{18}$$

using $h_{s_L}|^{post}$ (that is, equation (17)) and the fact that ΔL is well constrained from observations.

Generating the PDF of the null hypothesis $p_L|^{null}$. We evaluate the observed glacier retreat against a null hypothesis of no climate change. For no climate trend the PDF of s_b ($\equiv h_{s_b}|^{null}$) is governed by the standard Student's t-distribution centred on zero[24]. That is, equation (13) with $\overline{\Delta b}=0$. Thus, the PDF of the null hypothesis for s_L, $h_{s_L}|^{null}$, is calculated from the relationship $s_L=\gamma\cdot s_b$ and combining h_γ and $h_{s_L}|^{null}$.

Finally, we have $\Delta L=\sigma_L\cdot s_L$, and so the PDF of the null hypothesis for ΔL ($\equiv h_{\Delta L}|^{null}$) comes from combining h_{σ_L} and $h_{s_L}|^{null}$. We confirmed the validity of our calculations of $h_{\Delta L}|^{null}$ by Monte Carlo methods: generating a PDF of ΔLs from 10,000 130-yr integrations of the three-stage glacier-length model driven by climate variability with no trend.

Examples for $h_{\Delta L}|^{null}$ are shown in Fig. 4 and in Supplementary Figs 3–8. Following the standard approach, we determine the statistical significance of a glacier's retreat by calculating the probability, $p_L|^{null}$, that a ΔL could be consistent with the null hypothesis and yet lie beyond the observed retreat.

Code availability. The three-stage glacier model code is available from: http://earthweb.ess.washington.edu/roe/GerardWeb/Home.html. All analyses were performed by implementing the equations presented in the paper, for the data sets documented above.

Data availability. The following data sets were used in this study: glacier mass balance from: http://dx.doi.org/10.5904/wgms-fog-2014-09; glacier mass-balance analysis from: doi:10.1007/s00382-016-3253-x; glacier-length records from: http://www.the-cryosphere.net/8/659/2014/tc-8-659-2014-supplement.zip; Legates and Willmott precipitation data available from: http://www.esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html; Berkeley Earth temperature data available from: http://www.berkeleyearth.org/data. Other glacier parameters were taken from studies cited in the paper, and are documented in the Supplementary Information and in an accompanying spreadsheet.

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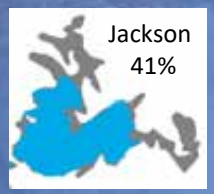
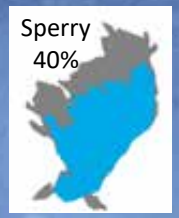
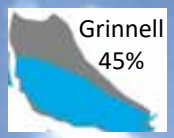
Losing a Namesake

Jackson Glacier, seen here from several miles away, has lost 41% of its area since 1966. In 1850 there were about 150 glaciers throughout the park, but today only 26 remain. Using a combination of historic maps and satellite imagery, scientists mapped these remaining glaciers. Check out the way glacier area changed. Retreat varied between individual glaciers, but the overall pattern is the same: Glaciers in Glacier National have shrunk, quite dramatically in some cases. This is consistent with the retreat of glaciers world wide, much of which is due to human-caused climate change.

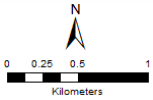




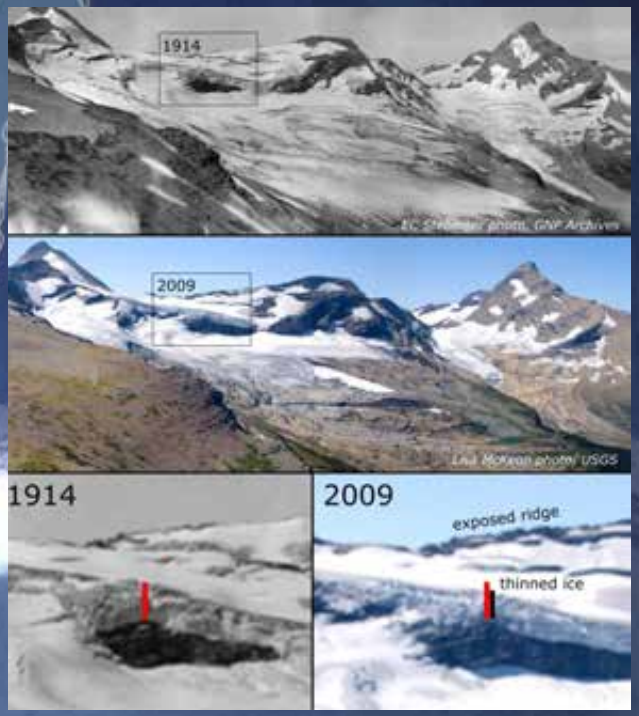


Order glaciers largest to smallest?
North to south?
Alphabetically?

1966 Glacier Extent



2015 Glacier Extent



Glaciers in 3D | The area change figures to the left only show two dimensions of glacier change, but in reality glaciers are massive and three dimensional. Look closely at the photos of Blackfoot and Jackson Glaciers in 1914 and 2009. Can you spot how the glacier has thinned?

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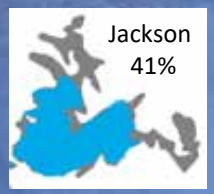

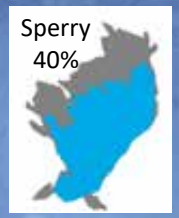

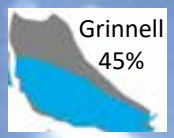

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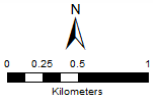

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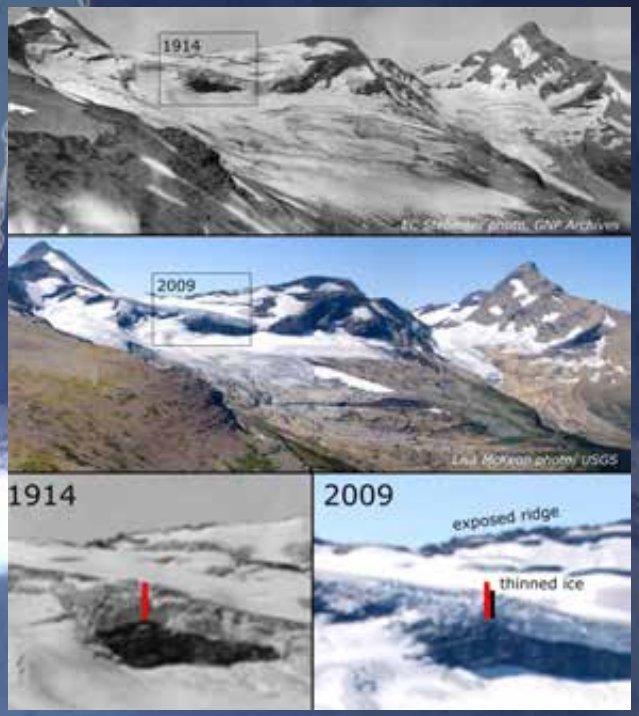

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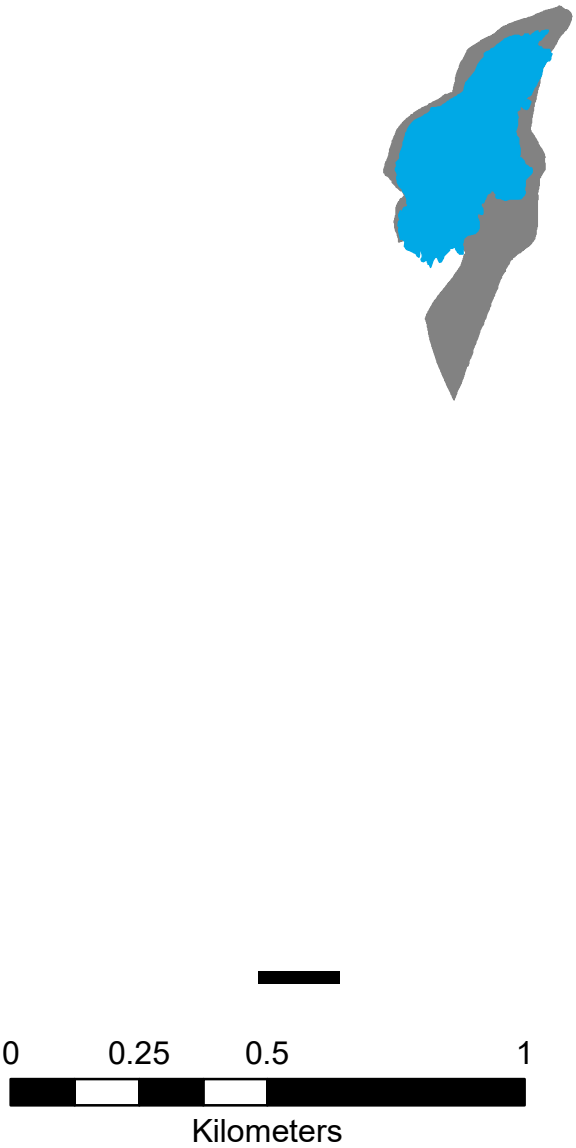
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Glacier Name_GNP	Area1966 (m²)	Area1998 (m²)	Area2005 (m²)	Area2015 (m²)	% Change 1966-2015
Agassiz Glacier	1,600,559.73	1,174,485.68	1,039,612.34	736,669.75	-53.97
Ahern Glacier	589,185.63	516,658.66	511,939.47	511,589.79	-13.17
Baby Glacier	117,171.13	80,880.38	76,006.47	75,562.60	-35.51
Blackfoot Glacier	1,832,451.35	1,625,124.38	1,630,173.41	1,498,505.92	-18.22
Boulder Glacier	231,017.73	48,774.13	45,803.63	35,298.01	-84.72
Carter Glacier	355,743.44	269,013.88	234,414.36	224,773.89	-36.82
Chaney Glacier	563,819.03	430,372.02	359,686.58	334,484.90	-40.68
Dixon Glacier	291,142.05	166,983.60	162,669.91	125,831.13	-56.78
Gem Glacier**	29,140.12	23,756.51	23,527.27	22,156.68	-23.97
Grinnell Glacier	1,020,200.39	715,907.79	615,568.81	563,720.29	-44.74
Harris Glacier	148,501.60	40,263.73	38,969.10	34,260.89	-76.93
Harrison Glacier	2,059,376.84	1,846,232.52	1,697,714.47	1,661,456.75	-19.32
Herbst Glacier	170,234.16	50,794.78	40,856.01	31,886.02	-81.27
Hudson Glacier**	90,213.45	55,762.11	52,269.76	52,167.62	-42.17
Ipasha Glacier	328,608.60	228,254.45	195,800.97	194,738.75	-40.74
Jackson Glacier	1,280,508.24	811,857.45	803,342.15	756,864.10	-40.89
Kintla Glacier	1,309,016.20	972,884.73	931,213.70	877,726.05	-32.95
Logan Glacier	503,361.09	387,547.07	367,936.17	219,016.92	-56.49
Lupfer Glacier	126,375.83	66,661.16	63,843.53	73,274.68	-42.02
Miche Wabun	204,468.79	111,127.26	107,464.55	103,616.92	-49.32
North Swiftcurrent Glacier	116,675.97	84,546.10	90,181.52	86,305.30	-26.03
Old Sun Glacier	421,347.41	349,137.54	346,751.63	341,077.95	-19.05
Piegan Glacier	280,151.62	265,084.78	250,768.05	244,307.08	-12.79
Pumpelly Glacier	1,006,469.53	910,631.86	908,834.15	902,787.30	-10.30
Rainbow Glacier	1,430,411.36	1,120,814.92	1,089,977.46	1,053,376.03	-26.36
Red Eagle	134,709.82	77,923.58	77,923.53	63,685.24	-52.72
Salamander Glacier	229,028.19	181,688.65	173,617.99	176,108.77	-23.11
Sexton Glacier	400,493.53	324,011.87	312,762.43	298,681.73	-25.42
Shepard Glacier	250,678.82	91,584.19	75,248.66	70,739.49	-71.78
Siyeh Glacier	306,295.75	214,597.44	214,663.20	205,386.48	-32.95
Sperry Glacier	1,339,531.54	953,104.43	888,095.13	801,670.14	-40.15
Swiftcurrent Glacier	221,786.00	188,681.39	176,239.36	170,348.10	-23.19
Thunderbird Glacier	135,074.71	121,885.69	115,978.22	107,012.09	-20.78
Two Ocean Glacier	429,001.73	193,677.91	189,199.44	75,172.89	-82.48
Vulture Glacier	408,034.38	336,924.77	329,180.45	296,786.09	-27.26
Weasel Collar Glacier	558,088.21	507,418.42	506,575.45	499,734.76	-10.46
Whitecrow Glacier	242,488.01	124,759.84	112,799.23	103,824.86	-57.18

Glacier Name_GNP	Area1966 (acres)	Area1998 (acres)	Area2005 (acres)	Area2015 (acres)
Agassiz Glacier	395.5	290.2	256.9	182.0
Ahern Glacier	145.6	127.7	126.5	126.4
Baby Glacier	29.0	20.0	18.8	18.7
Blackfoot Glacier	452.8	401.6	402.8	370.3
Boulder Glacier	57.1	12.1	11.3	8.7
Carter Glacier	87.9	66.5	57.9	55.5
Chaney Glacier	139.3	106.3	88.9	82.7
Dixon Glacier	71.9	41.3	40.2	31.1
Gem Glacier**	7.2	5.9	5.8	5.5
Grinnell Glacier	252.1	176.9	152.1	139.3
Harris Glacier	36.7	9.9	9.6	8.5
Harrison Glacier	508.9	456.2	419.5	410.6
Herbst Glacier	42.1	12.6	10.1	7.9
Hudson Glacier**	22.3	13.8	12.9	12.9
Ipasha Glacier	81.2	56.4	48.4	48.1
Jackson Glacier	316.4	200.6	198.5	187.0
Kintla Glacier	323.5	240.4	230.1	216.9
Logan Glacier	124.4	95.8	90.9	54.1
Lupfer Glacier	31.2	16.5	15.8	18.1
Miche Wabun	50.5	27.5	26.6	25.6
North Swiftcurrent Glacier	28.8	20.9	22.3	21.3
Old Sun Glacier	104.1	86.3	85.7	84.3
Piegan Glacier	69.2	65.5	62.0	60.4
Pumpelly Glacier	248.7	225.0	224.6	223.1
Rainbow Glacier	353.5	277.0	269.3	260.3
Red Eagle	33.3	19.3	19.3	15.7
Salamander Glacier	56.6	44.9	42.9	43.5
Sexton Glacier	99.0	80.1	77.3	73.8
Shepard Glacier	61.9	22.6	18.6	17.5
Siyeh Glacier	75.7	53.0	53.0	50.8
Sperry Glacier	331.0	235.5	219.5	198.1
Swiftcurrent Glacier	54.8	46.6	43.5	42.1
Thunderbird Glacier	33.4	30.1	28.7	26.4
Two Ocean Glacier	106.0	47.9	46.8	18.6
Vulture Glacier	100.8	83.3	81.3	73.3
Weasel Collar Glacier	137.9	125.4	125.2	123.5
Whitecrow Glacier	59.9	30.8	27.9	25.7

Glacier Name_GNP	Area1966 (m²)	Area1998 (m²)	Area2005 (m²)	Area2015 (m²)	Change 1966-201
Agassiz Glacier	1,600,559.73	1,174,485.68	1,039,612.34	736,669.75	-53.97
Ahern Glacier	589,185.63	516,658.66	511,939.47	511,589.79	-13.17
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Blackfoot Glacier	1,832,451.35	1,625,124.38	1,630,173.41	1,498,505.92	-18.22
Boulder Glacier	231,017.73	48,774.13	45,803.63	35,298.01	-84.72
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Chaney Glacier	563,819.03	430,372.02	359,686.58	334,484.90	-40.68
Dixon Glacier	291,142.05	166,983.60	162,669.91	125,831.13	-56.78
Gem Glacier**	29,140.12	23,756.51	23,527.27	22,156.68	-23.97
Grinnell Glacier	1,020,200.39	715,907.79	615,568.81	563,720.29	-44.74
Harris Glacier	148,501.60	40,263.73	38,969.10	34,260.89	-76.93
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Pumpelly Glacier	1,006,469.53	910,631.86	908,834.15	902,787.30	-10.30
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Red Eagle	134,709.82	77,923.58	77,923.53	63,685.24	-52.72
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Baby Glacier	29.0	20.0	18.8	18.7
Blackfoot Glacier	452.8	401.6	402.8	370.3
Boulder Glacier	57.1	12.1	11.3	8.7
Carter Glacier	87.9	66.5	57.9	55.5
Chaney Glacier	139.3	106.3	88.9	82.7
Dixon Glacier	71.9	41.3	40.2	31.1
Gem Glacier**	7.2	5.9	5.8	5.5
Grinnell Glacier	252.1	176.9	152.1	139.3
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Red Eagle	33.3	19.3	19.3	15.7
Salamander Glacier	56.6	44.9	42.9	43.5
Sexton Glacier	99.0	80.1	77.3	73.8
Shepard Glacier	61.9	22.6	18.6	17.5
Siyeh Glacier	75.7	53.0	53.0	50.8
Sperry Glacier	331.0	235.5	219.5	198.1
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Lupfer Glacier	126,375.83	66,661.16	63,843.53	73,274.68	-42.02
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Pumpelly Glacier	1,006,469.53	910,631.86	908,834.15	902,787.30	-10.30
Rainbow Glacier	1,430,411.36	1,120,814.92	1,089,977.46	1,053,376.03	-26.36
Red Eagle	134,709.82	77,923.58	77,923.53	63,685.24	-52.72
Salamander Glacier	229,028.19	181,688.65	173,617.99	176,108.77	-23.11
Sexton Glacier	400,493.53	324,011.87	312,762.43	298,681.73	-25.42
Shepard Glacier	250,678.82	91,584.19	75,248.66	70,739.49	-71.78
Siyeh Glacier	306,295.75	214,597.44	214,663.20	205,386.48	-32.95
Sperry Glacier	1,339,531.54	953,104.43	888,095.13	801,670.14	-40.15
Swiftcurrent Glacier	221,786.00	188,681.39	176,239.36	170,348.10	-23.19
Thunderbird Glacier	135,074.71	121,885.69	115,978.22	107,012.09	-20.78
Two Ocean Glacier	429,001.73	193,677.91	189,199.44	75,172.89	-82.48
Vulture Glacier	408,034.38	336,924.77	329,180.45	296,786.09	-27.26
Weasel Collar Glacier	558,088.21	507,418.42	506,575.45	499,734.76	-10.46
Whitecrow Glacier	242,488.01	124,759.84	112,799.23	103,824.86	-57.18

Glacier Name_GNP	Area1966 (acres)	Area1998 (acres)	Area2005 (acres)	Area2015 (acres)
Agassiz Glacier	395.5	290.2	256.9	182.0
Ahern Glacier	145.6	127.7	126.5	126.4
Baby Glacier	29.0	20.0	18.8	18.7
Blackfoot Glacier	452.8	401.6	402.8	370.3
Boulder Glacier	57.1	12.1	11.3	8.7
Carter Glacier	87.9	66.5	57.9	55.5
Chaney Glacier	139.3	106.3	88.9	82.7
Dixon Glacier	71.9	41.3	40.2	31.1
Gem Glacier**	7.2	5.9	5.8	5.5
Grinnell Glacier	252.1	176.9	152.1	139.3
Harris Glacier	36.7	9.9	9.6	8.5
Harrison Glacier	508.9	456.2	419.5	410.6
Herbst Glacier	42.1	12.6	10.1	7.9
Hudson Glacier**	22.3	13.8	12.9	12.9
Ipasha Glacier	81.2	56.4	48.4	48.1
Jackson Glacier	316.4	200.6	198.5	187.0
Kintla Glacier	323.5	240.4	230.1	216.9
Logan Glacier	124.4	95.8	90.9	54.1
Lupfer Glacier	31.2	16.5	15.8	18.1
Miche Wabun	50.5	27.5	26.6	25.6
North Swiftcurrent Glacier	28.8	20.9	22.3	21.3
Old Sun Glacier	104.1	86.3	85.7	84.3
Piegan Glacier	69.2	65.5	62.0	60.4
Pumpelly Glacier	248.7	225.0	224.6	223.1
Rainbow Glacier	353.5	277.0	269.3	260.3
Red Eagle	33.3	19.3	19.3	15.7
Salamander Glacier	56.6	44.9	42.9	43.5
Sexton Glacier	99.0	80.1	77.3	73.8
Shepard Glacier	61.9	22.6	18.6	17.5
Siyeh Glacier	75.7	53.0	53.0	50.8
Sperry Glacier	331.0	235.5	219.5	198.1
Swiftcurrent Glacier	54.8	46.6	43.5	42.1
Thunderbird Glacier	33.4	30.1	28.7	26.4
Two Ocean Glacier	106.0	47.9	46.8	18.6
Vulture Glacier	100.8	83.3	81.3	73.3
Weasel Collar Glacier	137.9	125.4	125.2	123.5
Whitecrow Glacier	59.9	30.8	27.9	25.7

Glacier Name_GNP	Area1966 (m²)	Area1998 (m²)	Area2005 (m²)	Area2015 (m²)	Change 1966-201
Agassiz Glacier	1,600,559.73	1,174,485.68	1,039,612.34	736,669.75	-53.97
Ahern Glacier	589,185.63	516,658.66	511,939.47	511,589.79	-13.17
Baby Glacier	117,171.13	80,880.38	76,006.47	75,562.60	-35.51
Blackfoot Glacier	1,832,451.35	1,625,124.38	1,630,173.41	1,498,505.92	-18.22
Boulder Glacier	231,017.73	48,774.13	45,803.63	35,298.01	-84.72
Carter Glacier	355,743.44	269,013.88	234,414.36	224,773.89	-36.82
Chaney Glacier	563,819.03	430,372.02	359,686.58	334,484.90	-40.68
Dixon Glacier	291,142.05	166,983.60	162,669.91	125,831.13	-56.78
Gem Glacier**	29,140.12	23,756.51	23,527.27	22,156.68	-23.97
Grinnell Glacier	1,020,200.39	715,907.79	615,568.81	563,720.29	-44.74
Harris Glacier	148,501.60	40,263.73	38,969.10	34,260.89	-76.93
Harrison Glacier	2,059,376.84	1,846,232.52	1,697,714.47	1,661,456.75	-19.32
Herbst Glacier	170,234.16	50,794.78	40,856.01	31,886.02	-81.27
Hudson Glacier**	90,213.45	55,762.11	52,269.76	52,167.62	-42.17
Ipasha Glacier	328,608.60	228,254.45	195,800.97	194,738.75	-40.74
Jackson Glacier	1,280,508.24	811,857.45	803,342.15	756,864.10	-40.89
Kintla Glacier	1,309,016.20	972,884.73	931,213.70	877,726.05	-32.95
Logan Glacier	503,361.09	387,547.07	367,936.17	219,016.92	-56.49
Lupfer Glacier	126,375.83	66,661.16	63,843.53	73,274.68	-42.02
Miche Wabun	204,468.79	111,127.26	107,464.55	103,616.92	-49.32
North Swiftcurrent Gl	116,675.97	84,546.10	90,181.52	86,305.30	-26.03
Old Sun Glacier	421,347.41	349,137.54	346,751.63	341,077.95	-19.05
Piegan Glacier	280,151.62	265,084.78	250,768.05	244,307.08	-12.79
Pumpelly Glacier	1,006,469.53	910,631.86	908,834.15	902,787.30	-10.30
Rainbow Glacier	1,430,411.36	1,120,814.92	1,089,977.46	1,053,376.03	-26.36
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Losing a Namesake

How many Glaciers will be left for the next Generation?

JACKSON GLACIER

These shapes outline the area of all the park's glaciers that existed in 1966. Jackson Glacier was 316 acres in 1966 and melted down to 187 acres by 2015.

Glacier footprint in 1966

Glacier footprint in 2015

No one can say for certain how much longer glaciers will be here, but scientists are closely studying the rate of glacial melt. There were over 100 glaciers here when the park was established in 1910. By 1966, 35 glaciers remained. In 2015, only 26 met the definition of an active glacier.

An active glacier is massive enough to move under its own weight and is usually at least 25 acres. Snow and ice remain long after a glacier stops meeting the scientific requirement of movement and size.

Every glacier in the park is shrinking. How many glaciers will be left for the next generation?

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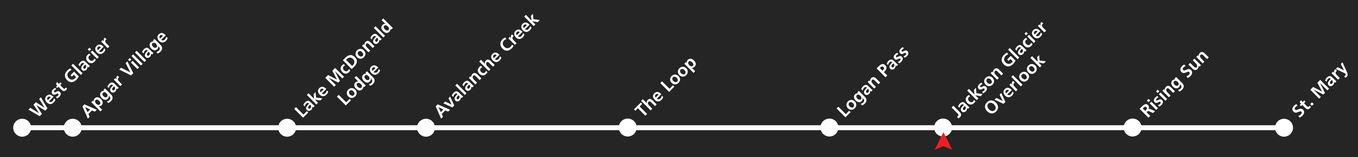
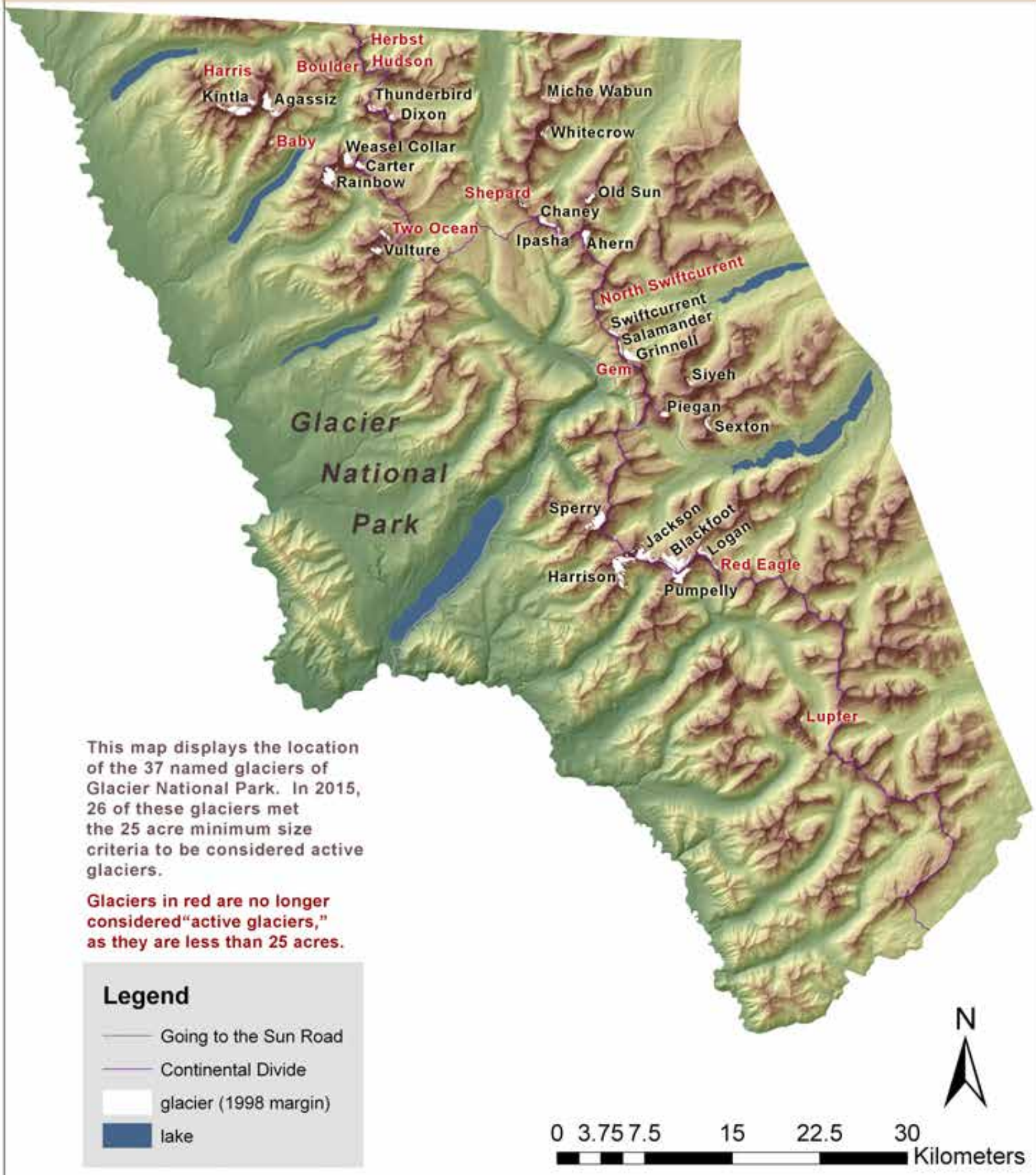


ELEVATION		
Logan Pass	6646 ft	2026 m
Current Location	5281 ft	1610 m
West Glacier	3225 ft	983 m

DIRECTION

DISTANCE		
West Glacier	36.7 mi	59.0 km
Logan Pass	4.7 mi	7.5 km
St. Mary	13.3 mi	21.4 km

Named Glaciers of Glacier National Park, MT



This map displays the location of the 37 named glaciers of Glacier National Park. In 2015, 26 of these glaciers met the 25 acre minimum size criteria to be considered active glaciers.

Glaciers in red are no longer considered "active glaciers," as they are less than 25 acres.

Legend

- Going to the Sun Road
- Continental Divide
- glacier (1998 margin)
- lake

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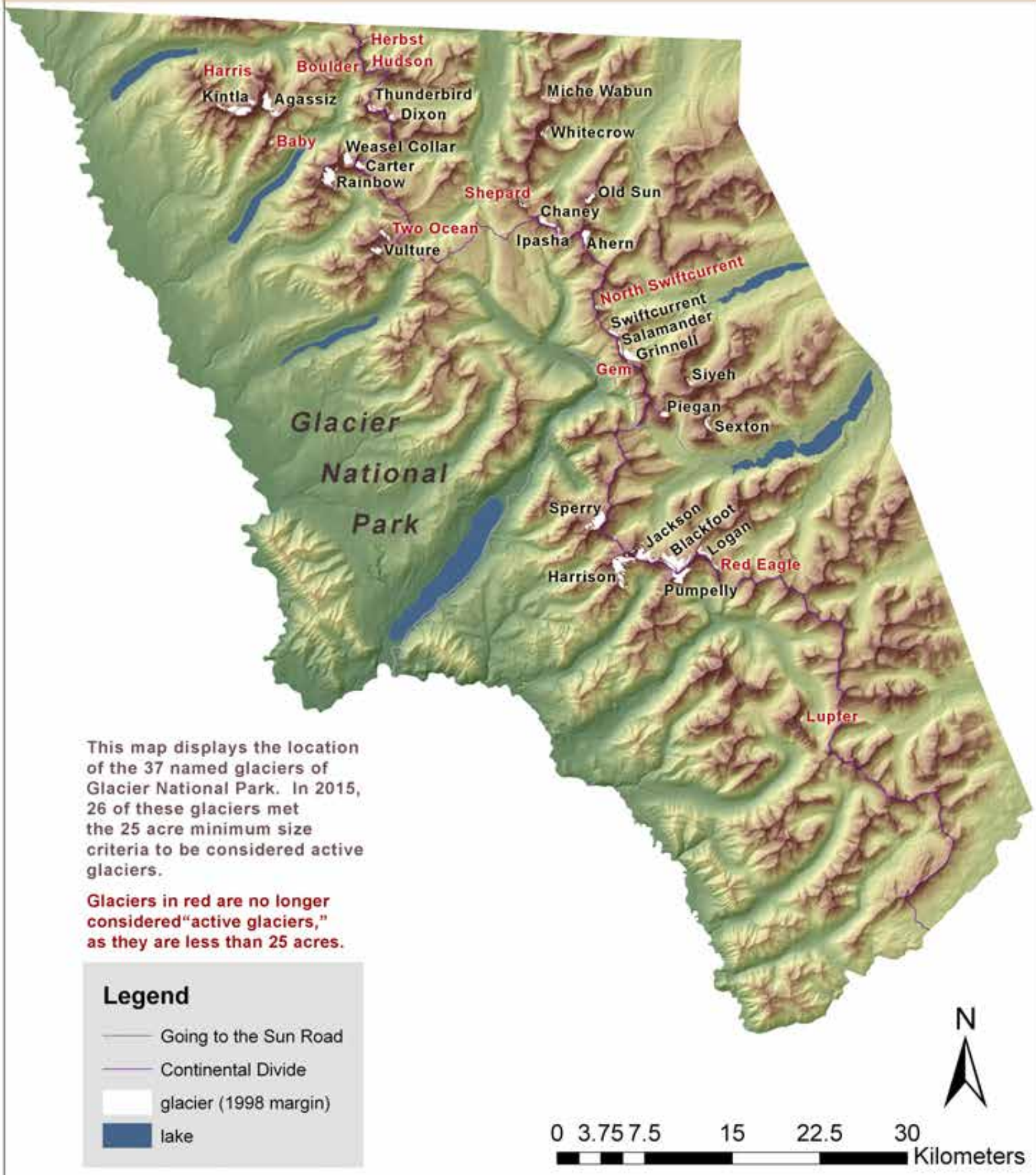

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Changing with the Times

Glaciers have come and gone for millennia, but never like this.

Do you see a glacier? From a distance, Jackson Glacier (pictured at right) is often indistinguishable from snowfields until the annual snowfall melts away. As the global climate warms, however, the glaciers are melting as well.

We know that glaciers have come and gone throughout Earth's history. We also know that whenever the amount of carbon dioxide (CO_2) in the atmosphere goes up, the temperature of Earth also rises and the glaciers melt.

What's different now is the speed at which the climate is changing. In the past century humans have put an unprecedented amount of CO_2 in the atmosphere and Earth is warming at a correspondingly alarming rate—much faster than any other time in the last 400,000 years.

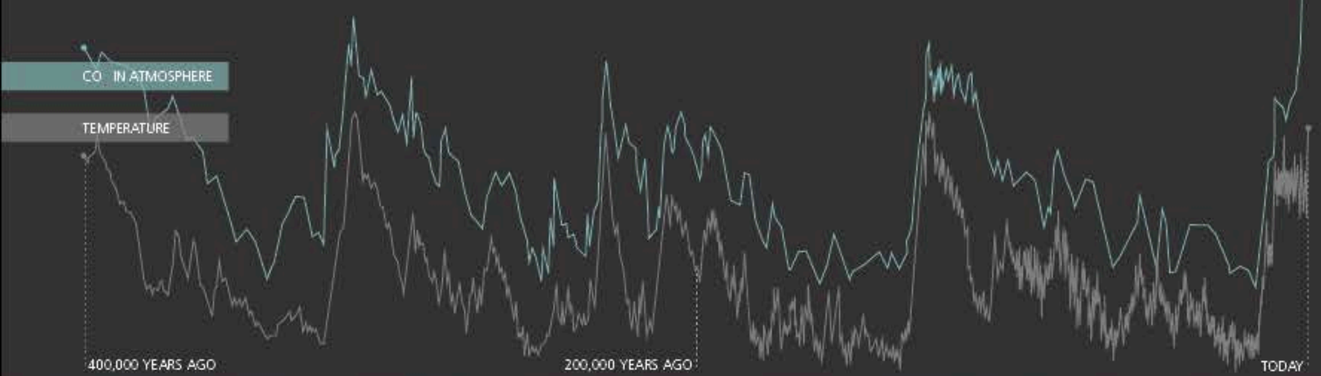

Photo by Morton J. Elrod, in 1911. Taken from the K. Ross Toole Archives at the University of Montana.

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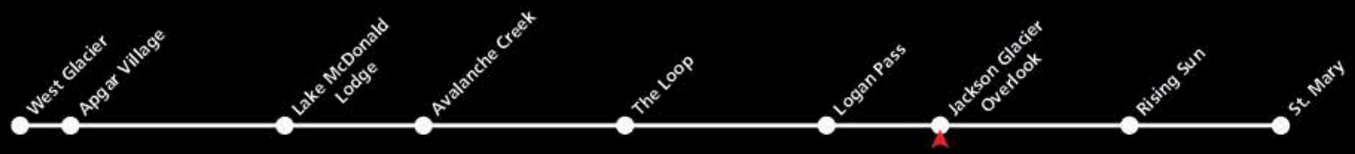

ELEVATION		
Logan Pass	6646 ft	2026 m
Current Location	5281 ft	1610 m
St. Mary	4551 ft	1387 m

DIRECTION

DISTANCE		
West Glacier	36.5 mi	58.7 km
Logan Pass	4.7 mi	7.5 km
St. Mary	13.5 mi	21.7 km

Losing a Namesake

How many glaciers will be left for the next generation?

JACKSON GLACIER

Jackson Glacier was 316 acres in 1966.
By 2015, it melted down to 187 acres.

GLACIER AREA IN 1966

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Every glacier in the park is rapidly shrinking, and no one can say for certain how much longer they will last, but scientists are closely studying the rate of melting. There were over 100 glaciers here when the park was established in 1910. By 1966, 35 glaciers remained. In 2015, only 26 met the definition of an active glacier.

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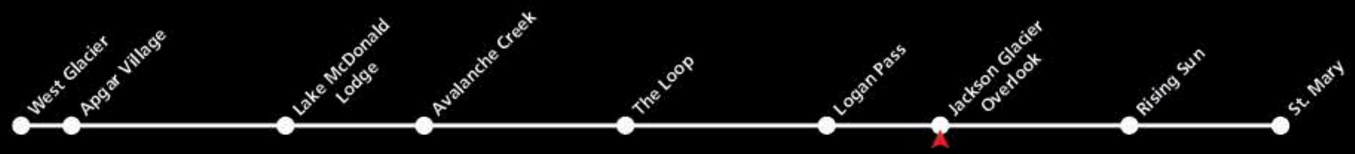

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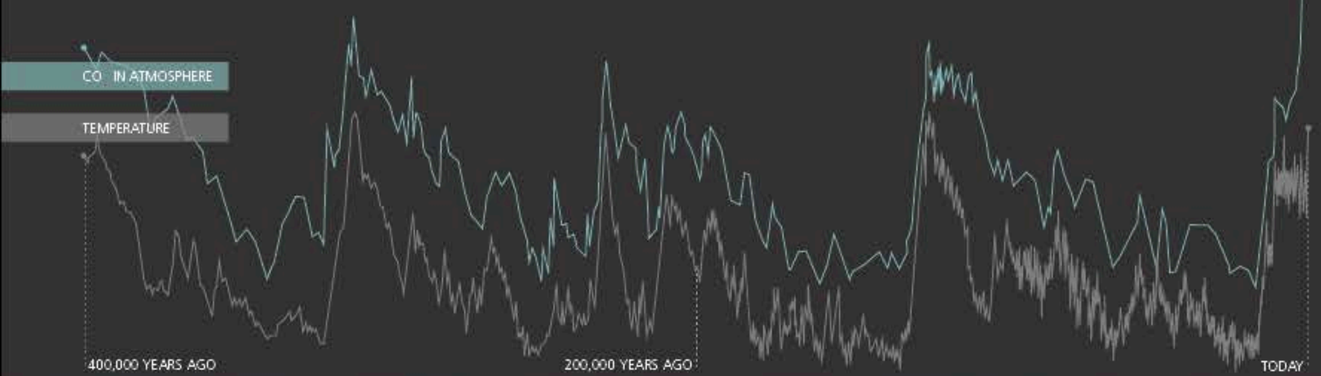

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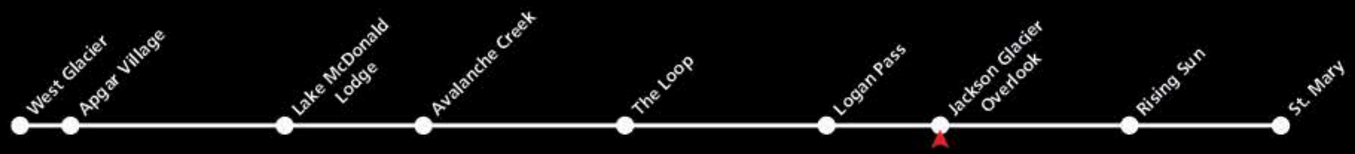

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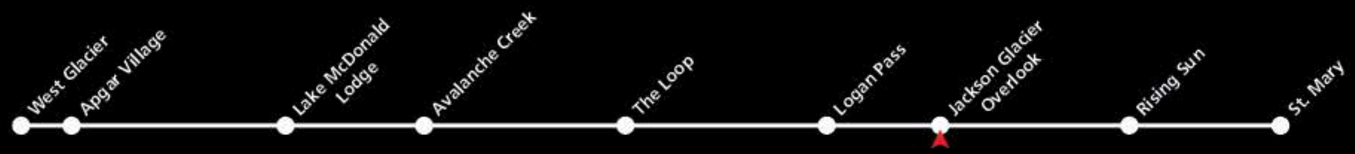

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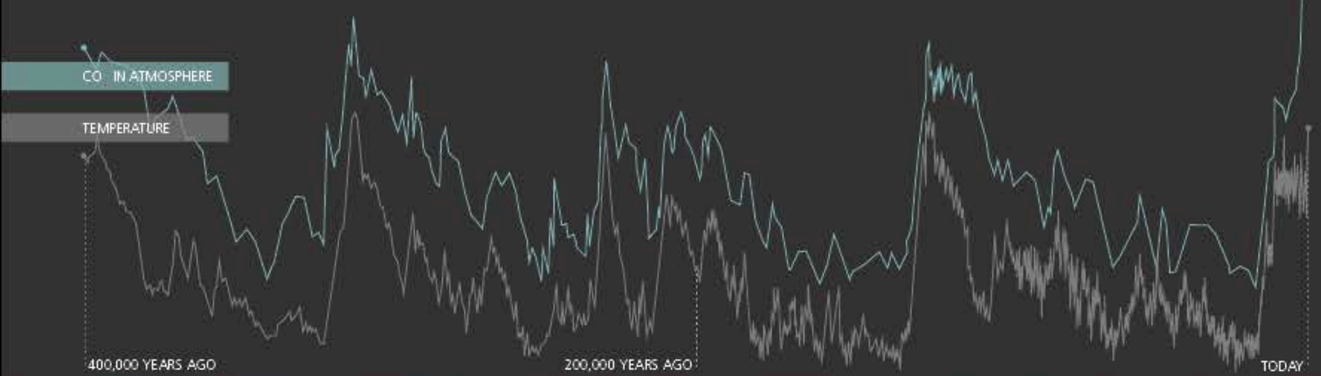

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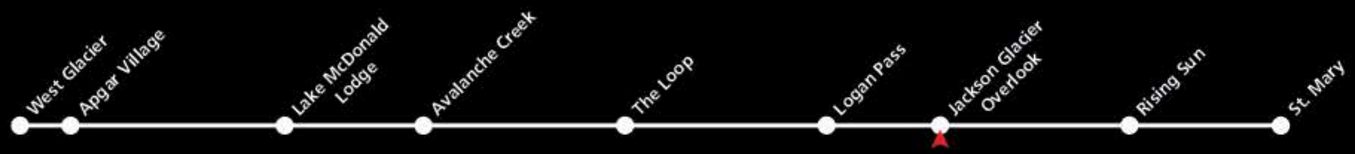

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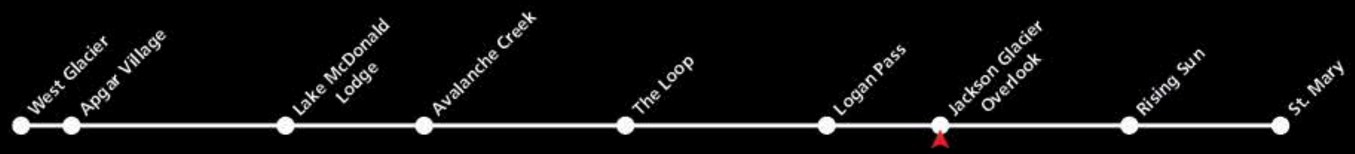

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Conversation Contents

If visitors ask when the glaciers will be gone:

Attachments:

/1. If visitors ask when the glaciers will be gone:/1.1 STMARY-VC-EXHIBIT-1-OLD.png
/1. If visitors ask when the glaciers will be gone:/1.2 STMARY-VC-EXHIBIT-1-UPDATED.png
/1. If visitors ask when the glaciers will be gone:/1.3 STMARY-VC-EXHIBIT-2-OLD.png
/1. If visitors ask when the glaciers will be gone:/1.4 STMARY-VC-EXHIBIT-2-UPDATED.png

"Lombardi, Daniel" <daniel_lombardi@nps.gov>

From:	"Lombardi, Daniel" <daniel_lombardi@nps.gov>
Sent:	Fri Jun 14 2019 11:49:40 GMT-0600 (MDT)
To:	Marc Neidig <marc_neidig@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>
CC:	William Hayden <bill_hayden@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>
Subject:	If visitors ask when the glaciers will be gone:
Attachments:	STMARY-VC-EXHIBIT-1-OLD.png STMARY-VC-EXHIBIT-1-UPDATED.png STMARY-VC-EXHIBIT-2-OLD.png STMARY-VC-EXHIBIT-2-UPDATED.png

If visitors ask when the glaciers will be gone:
Data show that in 1966, the park had 35 named glaciers large enough to be considered active. By 2015, only 26 named glaciers remained in that category. The average area reduction was 39 percent, though some lost as much as 85 percent. This trend of glacier retreat is expected to continue as temperatures rise. Some small remnant ice may persist late into the 21st century or even beyond, depending on future rates of climate change.

These updated webpages are your best secondary sources for information on the park's glaciers:

- https://www.nps.gov/glac/learn/nature/melting-glaciers.htm
- https://www.nps.gov/glac/learn/nature/how-to-see-a-glacier.htm
- https://www.nps.gov/glac/learn/nature/glacial-geology.htm

Background on previously used prediction dates:
A USGS geospatial model published in a 2003 paper predicted that Blackfoot and Jackson would be gone by 2030. Because these are two of the larger glaciers in the park (2nd and 6th respectively in 1966), it was extrapolated that if they were gone, the rest of the glaciers in the park would be gone too. The predicted date of 2030 was put on several exhibits throughout the park, including in the Apgar and St. Mary Visitor Center plazas.

Further research in the late 2000s (page 80) revealed that Jackson and Blackfoot glaciers were melting even faster than the rate predicted in the 2003 geospatial model. So fast, in fact, that if the rate continued they would be gone by 2020. It was then extrapolated that if Blackfoot and Jackson were gone by 2020, the rest of the glaciers in the park would be gone too. The 2020 date was then put on two exhibits outside the Logan Pass Visitor Center and on two exhibits inside the St. Mary Visitor Center (see below).

In May, 2019 the St. Mary Visitor Center exhibits were updated to reflect the analyses, data, and insights that have emerged since 2010. This latest research shows shrinking of all the park's glaciers but in ways far more complicated, and interesting, than expressed in the early 2000s. In the three places that used the 2020 date, the exhibits now say: *"Future Generations;" "When they will completely disappear, however, depends on how and when we act;"* and *"Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking."* (See images below.)

There are plans to update all the other exhibits (at the Logan Pass, Apgar, and St. Mary visitor centers) that use the 2020 and 2030 dates as time and funding allows.

STMARY-VC-EXHIBIT-1-OLD.png
STMARY-VC-EXHIBIT-1-UPDATED.png
STMARY-VC-EXHIBIT-2-OLD.png
STMARY-VC-EXHIBIT-2-UPDATED.png

Conversation Contents

Re: [EXTERNAL] Wash Times inquiry/Glacier National Park Signage

"Alley, Lauren" <lauren_alley@nps.gov>

From:	"Alley, Lauren" <lauren_alley@nps.gov>
Sent:	Mon Jun 10 2019 13:57:23 GMT-0600 (MDT)
To:	"Kupper, Kathy" <kathy_kupper@nps.gov>
CC:	"Puckett, Catherine" <cpuckett@usgs.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, "McClymont, Ryan" <rmcclymont@usgs.gov>, "Armstrong, Karen" <karmstrong@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Re: [EXTERNAL] Wash Times inquiry/Glacier National Park Signage

Kathy -

The park has a number of interpretive exhibits about glaciers, some of which contain information based on early glacial recession research and modeling. Those will be updated as capacity and funding allows, similar to other outdated exhibits on other topics.

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

On Mon, Jun 10, 2019 at 12:39 PM Kupper, Kathy <kathy_kupper@nps.gov> wrote:

> Hi All,
>
> I did respond to the reporter with the statement. In a follow up she asked if I could confirm that the park is removing the "2020" signs. Have they already been removed or will they be?
>
> Thank you,
> Kathy
>
> Kathy Kupper
> Public Affairs Specialist
> Office of Communications
> National Park Service
> (202)513-7263
> www.nps.gov

The National Park Service cares for special places saved by the American people so that all may experience our heritage.

EXPERIENCE YOUR AMERICA ®

On Mon, Jun 10, 2019 at 1:37 PM Puckett, Catherine <cpuckett@usgs.gov> wrote:

> *Hi Kathy: I've been copied on the various GNP, glaciers, and signage emails among USGS (Dan Fagre and Karen Armstrong), reporters, and Molly at DOI Comms.*
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> *Since this one below from the Washington Times is about signage, I think it is in NPS's lane to respond using Molly's desk statement. Does this work? Please let me know if you can respond to the reporter.*
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> *Catherine*
> *Statement*
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> Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.
>
> The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.
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>
> ----------
>
> Catherine Puckett
> Acting Western States Communications Chief
> USGS Office of Communications
> 352-377-2469 (O) 352-278-0165 (cell)
> cpuckett@usgs.gov

On Mon, Jun 10, 2019 at 11:50 AM Valerie Richardson <vrichardson@washingtontimes.com> wrote:

> Hi, I wanted to see if Glacier National Park is actually removing signs saying that it would disappear underwater by 2020, as reported, and if so, why that is.
>
> Here's a report on Watts Up With That:
>
> https://wattsupwiththat.com/2019/06/07/glacier-national-park-quietly-removes-its-gone-by-2020-signs/
>
> Thanks very much,
>
> Valerie

--
Valerie Richardson | National Reporter / Denver and Omaha
cell 303-507-3856 | office 303.470.7078 | @ValRichardson17

The Washington Times
3600 New York Ave NE | Washington DC, 20002
washingtontimes.com

The information contained in this electronic transmission is intended for the exclusive use of the individuals to whom it is addressed and may contain information that is privileged and confidential, the disclosure of which is prohibited by law. If the reader of this transmission is not the intended recipient, you are hereby notified that any dissemination, distribution or copying of this communication is strictly prohibited. In addition, any unauthorized copying, disclosure or distribution of the material in this e-mail and any attachments is strictly forbidden.

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CC:	"Puckett, Catherine" <cpuckett@usgs.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, "McClymont, Ryan" <rmcclymont@usgs.gov>, "Armstrong, Karen" <karmstrong@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Re: [EXTERNAL] Wash Times inquiry/Glacier National Park Signage

Thanks Lauren!

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
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Thanks very much,

Valerie

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Valerie Richardson | National Reporter / Denver and Omaha
cell 303-507-3856 | office 303.470.7078 | @ValRichardson17

The Washington Times
3600 New York Ave NE | Washington DC, 20002
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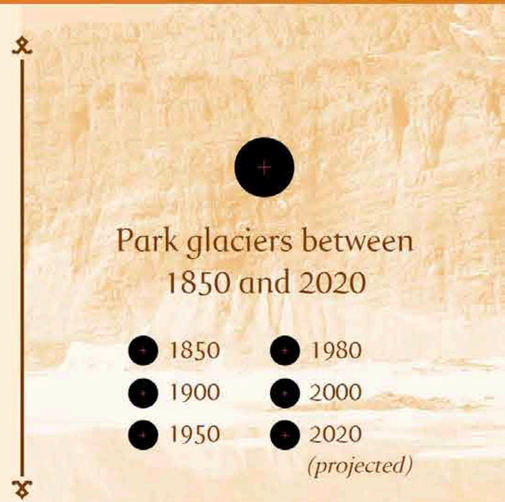
GOODBYE TO THE GLACIERS

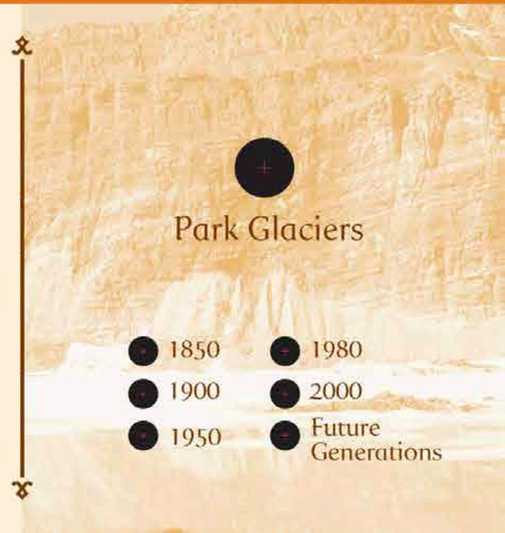
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum in size and number around 1850, at the end of the Little Ice Age. They are now rapidly shrinking due to human-caused climate change. Computer models indicate the glaciers will all be gone by the year 2020.

Glacier National Park was named for the sculpting actions of the Pleistocene glaciers that covered this landscape 12,000 to 130,000 years ago.



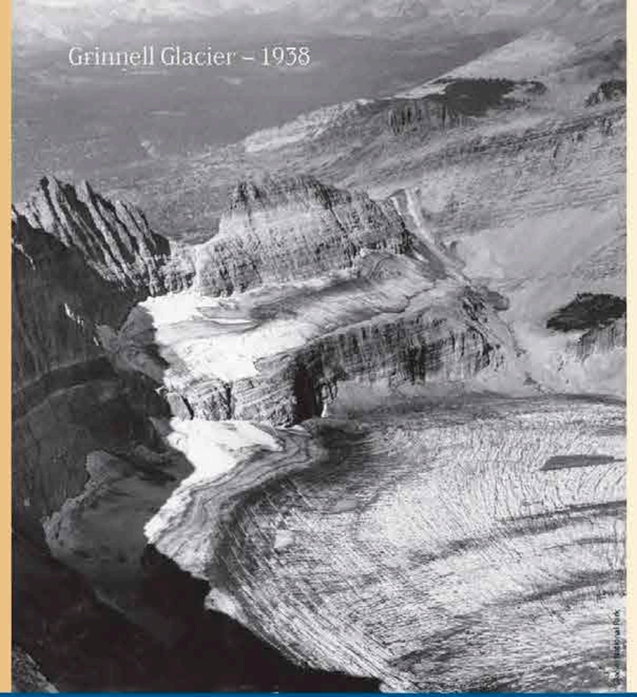
GOODBYE TO THE GLACIERS

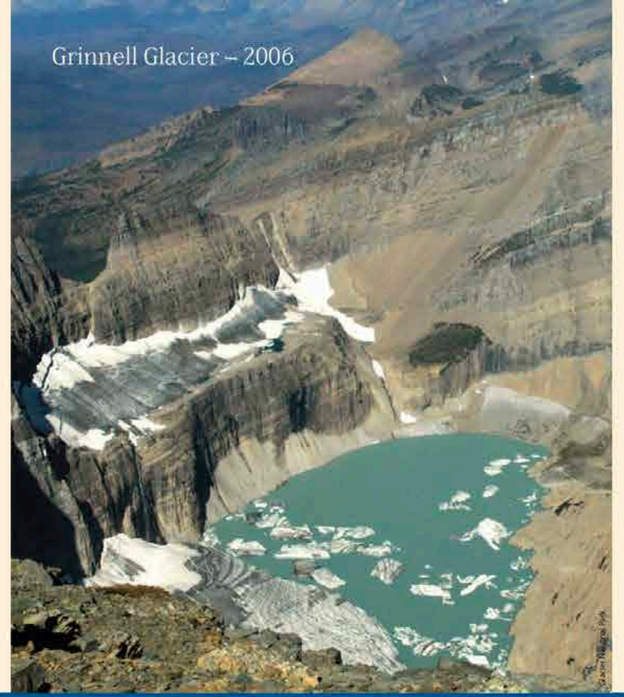
The small alpine glaciers present today started forming about 7,000 years ago and reached their maximum size and number around 1850, at the end of the Little Ice Age. Currently, they are rapidly shrinking due to human-accelerated climate change. When they will completely disappear, however, depends on how and when we act.



Glaciers are moving masses of ice. The glaciers that shaped the park were massive. During the pleistocene—12,000–130,000 years ago—the glaciers covering this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

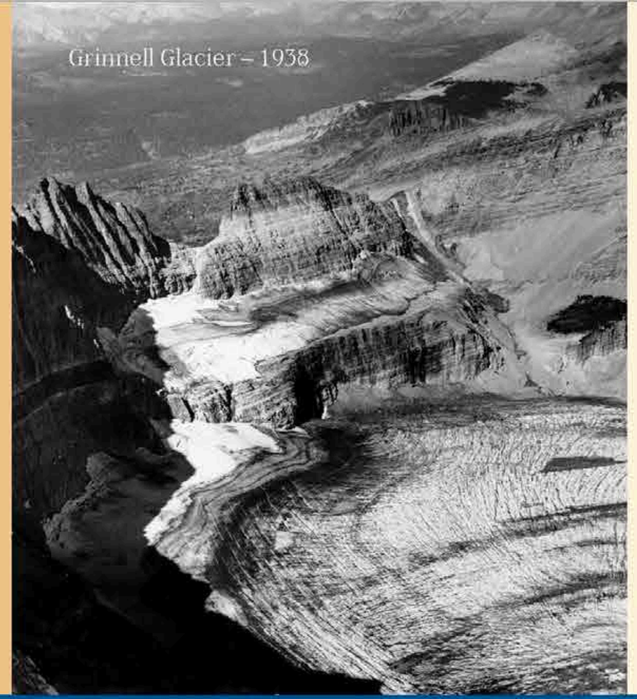
In 1850 there were 150 glaciers in the park; in 2010 the number decreased to 25. Current climate models suggest that all of the glaciers in Glacier National Park will be gone by 2020.

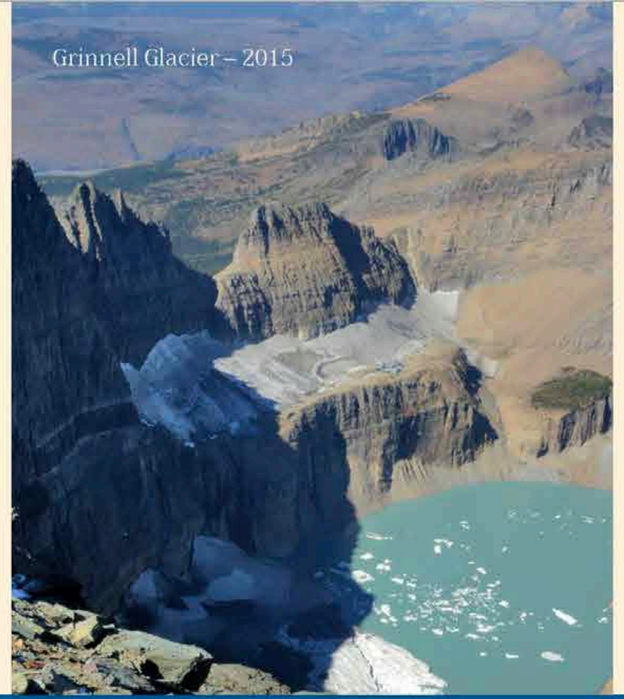
Grinnell Glacier, located high in the Many Glacier valley, has significantly retreated in recent decades.

GLACIERS ON THE MOVE

Glaciers are moving masses of ice. During the Pleistocene—12,000–130,000 years ago—the massive glaciers shaping this landscape were thousands of feet thick.

Glaciers are different from ice fields because they move—cutting away at the underlying rock and creating sharp ridges, U-shaped valleys, and alpine lakes.





Glaciers store large amounts of water for year-round use downstream. Plants and animals rely on melting waters from the glaciers to supply streams, rivers, and lakes.

In 1850 there were about 150 glaciers in the park. In 2015, only 26 named glaciers remained in the park.

Some glaciers melt faster than others, but one thing is consistent: the glaciers in the park are shrinking. Grinnell Glacier, located high in the Many Glacier Valley, has lost 45% of its area in recent decades.

GLACIERS ON THE MOVE

Conversation Contents

Exhibit text and/or photos ASAP?

Attachments:

/3. Exhibit text and/or photos ASAP?/2.1 GL-07-400rev2.pdf
/3. Exhibit text and/or photos ASAP?/2.2 GL-07-400 May 2019 Revisions.pdf
/3. Exhibit text and/or photos ASAP?/2.3 GL-06-300 updated MAY 2019.pdf
/3. Exhibit text and/or photos ASAP?/2.4 GL-06-300rev1.pdf
/3. Exhibit text and/or photos ASAP?/3.1 GL-07-400rev2.pdf
/3. Exhibit text and/or photos ASAP?/3.2 GL-07-400 May 2019 Revisions.pdf
/3. Exhibit text and/or photos ASAP?/3.3 GL-06-300 updated MAY 2019.pdf
/3. Exhibit text and/or photos ASAP?/3.4 GL-06-300rev1.pdf

Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Sat Jun 08 2019 15:05:54 GMT-0600 (MDT)
To:	lee_rademaker@nps.gov, debby_smith@nps.gov
CC:	Bill_Hayden@nps.gov, tracy_ammerman@nps.gov
Subject:	Exhibit text and/or photos ASAP?

Hey Lee and Debby - Are either of you working today or tomorrow? There are some media outlets reporting about our Glacier exhibit updates and I'd like to get a sense of how things looked before and after so we can put some info on the web if needed to clear up confusion. My guess is that by Monday morning, main stream media will be calling. If you have text or photos or anything, I would really appreciate it. Cc to Tracy and Bill as well. Thanks all. Sent from my iPad

"Hayden, William" <bill_hayden@nps.gov>

From:	"Hayden, William" <bill_hayden@nps.gov>
Sent:	Sat Jun 08 2019 16:20:37 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	Lee Rademaker <lee_rademaker@nps.gov>, "Mensch, D" <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Re: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Here are some attachments and some background.

The exhibits in the St. Mary Visitor Center were probably installed in 2010. There had been several planning and design meetings with Harpers Ferry Center personnel in the several years

previous. Mark Wagner was the lead on the exhibit redesigns. Sheri Forbes was the Chief of Interpretation. I was actually not involved in any aspect of the project or meetings from start to finish, so my memory on the exact dates is fuzzy. My guess on the year is based on the final planning document from the fabricator of the exhibits. The planning and design most surely happened much prior to that date. Mark Wagner may know more specifics.

In any case the exhibits that deal with glacial retreat were based on the USGS information that was available at that time. Since then their research has continued and evolved to include a more refined picture of glaciers in the park. Like much of scientific research, there are often not concrete black and white answers to basic questions, and that is often hard for some people to grapple with.

In the late summer, or fall, of 2017 staff from the USGS informed us, the media staff, that there were dates in the exhibits near the relief map at St. Mary that were not consistent with current research and asked that we change them. We were unable to do that for the 2018 season. At the end of the season we removed the exhibits and made changes to the original files. Those changes went through review by NPS and USGS staff and our sign shop was able to fabricate them and have them installed just prior to the opening of the Visitor Center this spring. Attached you should find the new exhibits and the former exhibits as PDF files.

There are also exhibits at the Apgar and St. Mary Visitor Center plazas, outside, that have dates that need changing. Those exhibits date from 2007. There are two exhibits that I know of at Logan Pass that likewise have these dates and should be changed out. In 2018 two new glacier exhibits replaced the one exhibit at Jackson Glacier Overlook. The old one had the 2030 date on it as well. It also contained images from the computer projection model, that was based on USGS work published in the early 2000s, I think 2003. This oldexhibit was designed in 2006 in coordination with Leigh Welling, who was in charge of the Crown of the Continent Research Learning Center at the time. I remember the date because I worked on refining her files while I was in Seattle that entire summer. She went from Glacier to a position in Colorado for the Natural Resources Division, where she dealt specifically with climate change issues.

A more complete review of other wayside exhibits will show mentions of climate change and some may have dates, although none come to mind at the moment. I can provide copies of these other exhibits if you wish, but I don't want to overload this particular email. We have them to view when needed.

Exhibit GL-07-400 May 2019 Revisions.pdf is the exhibit at the relief map that has the button to push for locations of the glaciers. It does not mention a specific date for the complete glacial melt. GL-07-400rev2.pdf is the original file as installed when the rest of the exhibits went in.

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Daniel/Tracy feel free to provide any details or updates that I may have missed or gotten wrong.

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Bill Hayden
Interpretive Specialist
Glacier National Park
West Glacier, MT 59936
406-888-7927

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Mon Jun 10 2019 08:00:57 GMT-0600 (MDT)
To:	"Mow, Jeff" <jeff_mow@nps.gov>, Connie Stahr <connie_stahr@nps.gov>
CC:	"Alley, Lauren" <lauren_alley@nps.gov>, Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Fwd: Exhibit text and/or photos ASAP?
Attachments:	GL-07-400rev2.pdf GL-07-400 May 2019 Revisions.pdf GL-06-300 updated MAY 2019.pdf GL-06-300rev1.pdf

Jeff,

For our discussion and your information. If we need additional detail in regard to timing, I could reach out to Mark Wagner and/or HFC.

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930

---------- Forwarded message ---------
From: **Hayden, William** <bill_hayden@nps.gov>
Date: Sat, Jun 8, 2019 at 4:20 PM
Subject: Re: Exhibit text and/or photos ASAP?
~~~~~~~~~~~~~~~~~~~~~~~~~

To: Lauren Alley <lauren_alley@nps.gov>
Cc: Lee Rademaker <lee_rademaker@nps.gov>, Mensch, D <debby_smith@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, Daniel Lombardi <daniel_lombardi@nps.gov>

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Conversation Contents

Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Attachments:

/4. Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage/1.1 image001.png
/4. Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage/1.2 image002.png

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To:	dan_fagre@usgs.gov, Melissa_Sladek@nps.gov, tara_carolin@nps.gov, jeff_mow@nps.gov, tracy_ammerman@nps.gov, phil_wilson@nps.gov
Subject:	Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage
Attachments:	image001.png image002.png

All -

I am circling back with you on what WASO and DOI have proposed below. From media outlets, it appears they're already using it (the stuff in gray text that the park didn't develop). The story has gone fairly viral in the last 24 hours.

Dan - do you want us to use this, or something else?

From park perspective I'm hoping to track down exhibit text so we can hopefully proactively address this.

My main objective is to identify exactly what NPS/USGS said about 2020 and publicly acknowledge that via website to clear up any confusion and for transparency. Certainly nobody wants to "quietly" do something or hide something. If anyone has any proposed text for this specific point, I'd welcome it.

Thanks to anyone who can provide input over the weekend. My guess is that by Monday at 8 am, we're going to get even more calls.

Sent from my iPad

Begin forwarded message:

> **From:** "Kupper, Kathy" <kathy_kupper@nps.gov>
> **Date:** June 7, 2019 at 3:24:56 PM MDT
> **To:** "Block, Molly" <molly_block@ios.doi.gov>
> **Cc:** April Slayton <april_slayton@nps.gov>, "Barnum, Jeremy" <jeremy_barnum@nps.gov>, Karen Armstrong <karmstrong@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon

<marco_deleon@nps.gov>, Paul Laustsen <plaustsen@usgs.gov>, Ryan McClymont <rmcclymont@usgs.gov>, Catherine Puckett <cpuckett@usgs.gov>
Subject: Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Hi Molly,

April and I are OK with the statement. We are looping in park staff and a couple of other SMEs for awareness and their input on the statement. Dan Fagre from USGS (dan_fagre@usgs.gov) is the SME that can also take calls if needed.

Thank you,
Kathy

Kathy Kupper
Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

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On Fri, Jun 7, 2019 at 5:00 PM Block, Molly <molly_block@ios.doi.gov> wrote:

> Adding the Park Service. Let's get a desk statement we can send around. Here's what I shared with the Daily Caller:
>
> Those signs were based on the observation prior to 2010 that glaciers were shrinking more quickly than a computer model predicted they would. Subsequently, larger than average snowfall over several winters slowed down that retreat rate and the 2020 date used in the NPS display does not apply anymore.
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>
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>
> The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.
>
> On Fri, Jun 7, 2019 at 4:53 PM Karen Armstrong <karmstrong@usgs.gov> wrote:
>
>> How would you like to handle?
>>
>> Sent from my iPhone
>>
>> Begin forwarded message:

From: Cheyenne MacDonald <Cheyenne.Macdonald@mailonline.com>
Date: June 7, 2019 at 4:48:07 PM EDT
To: "karmstrong@usgs.gov" <karmstrong@usgs.gov>
Subject: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Hi Karen! My name is Cheyenne, I'm the Science & Tech Editor at Dailymail.com. I'm reaching out in regards to a report that's been going around today, was hoping to get some additional context and verify the claims being made.

The report, linked here, https://dailycaller.com/2019/06/07/national-park-glacier-warnings/ , claims signs at Glacier National Park that warned glaciers will disappear by 2020 due to climate change have been 'quietly removed' after 'several winters of heavy snowfall threw off climate model projections.'

I would appreciate if you could clarify a few points:

-Have the signs really been changed? If so, when and why

-What do the latest models suggest about the state of glaciers in the park?

-Is there any weight to claims that glaciers have grown in recent years due to heavier snowfall?

Any additional information you can provide on the subject would be great.

Thanks so much.

Best,

Cheyenne

Cheyenne MacDonald

US Science & Technology Editor

Daily Mail Online | @_cheymac

51 Astor Place, 9th Floor, New York, NY 10003

cid:C0FFDDA4-A7B5-4A83-82B0-6D14B1369EE4

cid:1B9B73EA-D6E8-4333-8EAD-98E24A75B563

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--
Molly Block
Press Secretary
U.S. Department of the Interior

Jeff Mow <jeff_mow@nps.gov>

From:	Jeff Mow <jeff_mow@nps.gov>
Sent:	Sat Jun 08 2019 15:54:56 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
CC:	dan_fagre@usgs.gov, Melissa_Sladek@nps.gov, tara_carolin@nps.gov, tracy_ammerman@nps.gov, phil_wilson@nps.gov
Subject:	Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage

All

Debby and I touched base on this yesterday and we said we'd circle up on the process on Monday. A couple of things I'd like to know

1) how old are these exhibits
2) when did we put these into pmis for replacement funding
3) how many exhibits overall do we have in pmis for cyclic funding replacement
4) am I correct in assuming that the lion's share of exhibit panels that make reference to When the glaciers will disappear use the 2030 date. The 2020 date is an outlier.

To me there is a backstory that may have a connection to DM. We have so many trails, roads, restrooms, campgrounds, water systems, and wayside exhibits that are in line for replacement or rehabilitation and as we all know it can takes years for things to move up in the priority list.

I have no idea if these exhibits are in The system like the interpretive waysides are so this theme may not apply.

Sent from my iPhone

On Jun 8, 2019, at 3:12 PM, Lauren Alley <lauren_alley@nps.gov> wrote:

> All -
>
> I am circling back with you on what WASO and DOI have proposed below. From media outlets, it appears they're already using it (the stuff in gray text that the park didn't develop). The story has gone fairly viral in the last 24 hours.
>
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> My main objective is to identify exactly what NPS/USGS said about 2020 and publicly acknowledge that via website to clear up any confusion and for transparency. Certainly nobody wants to "quietly" do something or hide something. If anyone has any proposed text for this specific point, I'd welcome it.
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Cheyenne MacDonald

US Science & Technology Editor

Daily Mail Online | @_cheymac

51 Astor Place, 9th Floor, New York, NY 10003

<image001.png>

<image002.png>

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--
Molly Block
Press Secretary
U.S. Department of the Interior

"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Sat Jun 08 2019 16:31:30 GMT-0600 (MDT)
To:	Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Fwd: [EXTERNAL] Daily Mail Inquiry - National Park Signage

Bill,
Thank you so very much for the comprehensive information you provided in the other email you sent, with exhibit attachments. Note this email from Jeff and some of the additional information that he will also be looking for us to provide on Monday. In particular it is apparent that Jeff has an interest in seeing how these may associate with deferred maintenance and the maintenance backlog. You went above and beyond the call of duty today! Thank you so much!

---------- Forwarded message ---------
From: **Jeff Mow** <jeff_mow@nps.gov>
Date: Sat, Jun 8, 2019, 3:54 PM
Subject: Re: [EXTERNAL] Daily Mail Inquiry - National Park Signage
To: Lauren Alley <lauren_alley@nps.gov>
Cc: <dan_fagre@usgs.gov>, <Melissa_Sladek@nps.gov>, <tara_carolin@nps.gov>, <tracy_ammerman@nps.gov>, <phil_wilson@nps.gov>

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<image001.png>

<image002.png>

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--
Molly Block
Press Secretary
U.S. Department of the Interior

Conversation Contents

SMVC exhibit

Deborah Smith <debby_smith@nps.gov>

From:	Deborah Smith <debby_smith@nps.gov>
Sent:	Fri Jun 07 2019 19:22:30 GMT-0600 (MDT)
To:	Jeff Mow <jeff_mow@nps.gov>
CC:	Marc Neidig <marc_neidig@nps.gov>, Tracy Ammerman <Tracy_Ammerman@nps.gov>
Subject:	SMVC exhibit

Hi Jeff,

Marc just sent me a message about the SMVC exhibit and I'm wondering if it's related to this (see below). Before the start of the season, the two exhibit panels in SMVC related to climate change were updated to correct some outdated information. Daniel (in consultation with Bill, Lee, USGS, and myself) helped get them installed prior to opening, but this person has been on our radar and, unsurprisingly, he's already noticed and put it on the web. May be totally unrelated to your inquiry to Marc, but seems like a strange coincidence and thought you'd like to see this regardless.

Thanks for joining us today,
Debby

Debby Smith
Hudson Bay District Interpreter
Glacier National Park
73 Hudson Bay Road Unit 1
Browning, MT 59417
p: (406) 732-7757

-------- Original Message --------
From: "Lombardi, Daniel" <daniel_lombardi@nps.gov>
Date: Thu, June 06, 2019 1:34 PM -0600
To: Deborah Smith <debby_smith@nps.gov>, Lee Rademaker <lee_rademaker@nps.gov>, "Sine, Diane" <diane_sine@nps.gov>, William Hayden <bill_hayden@nps.gov>, Caitlyn Florentine <cflorentine@usgs.gov>, Lisa Mckeon <lisa_mckeon@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Melissa Sladek <melissa_sladek@nps.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>
Subject: That was quick...

The new St. Mary exhibits were noticed:

https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/

--
Daniel Lombardi
Visual Information Specialist
Glacier National Park
406-888-7933

Conversation Contents

Fwd: Media Inquiry: [EXTERNAL] Is this true?

"Mow, Jeff" <jeff_mow@nps.gov>

From:	"Mow, Jeff" <jeff_mow@nps.gov>
Sent:	Fri Jun 07 2019 14:45:41 GMT-0600 (MDT)
To:	Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

FYI,

Jeff Mow
Superintendent
Glacier National Park
P.O. Box 128
West Glacier, MT 59938
office: 406 888 7901
mobile: 406 250 1431
fax: 406 888 7904

---------- Forwarded message ---------
From: **Stahr, Connie** <connie_stahr@nps.gov>
Date: Fri, Jun 7, 2019 at 2:33 PM
Subject: Fwd: Media Inquiry: [EXTERNAL] Is this true?
To: Jeff Mow <jeff_mow@nps.gov>

FYI.....Tegan has been receiving a number of phone calls from irate visitors concerning this blog. Apparently Rush Limbaugh also aired a show concerning this blog.

Connie Stahr
Executive Assistant
Office of the Superintendent
Glacier National Park
P.O. Box 128
West Glacier, MT 59936
406-888-7901 Phone
406-888-7904 Fax

---------- Forwarded message ---------
From: **Tomlin, Teagan** <teagan_tomlin@nps.gov>
Date: Fri, Jun 7, 2019 at 2:16 PM
Subject: Fwd: Media Inquiry: [EXTERNAL] Is this true?
To: Connie Stahr <connie_stahr@nps.gov>

Hi Connie,

Below is the information I received from Lauren Alley. Here is the link to the original article that was picked up by Rush Limbaugh:

> https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc

Teagan Tomlin
Visitor Services Assistant
Glacier National Park
406-888-7931

---------- Forwarded message ---------
From: **Lauren Alley** <lauren_alley@nps.gov>
Date: Fri, Jun 7, 2019 at 1:57 PM
Subject: Fwd: Media Inquiry: [EXTERNAL] Is this true?
To: <teagan_tomlin@nps.gov>

Sent from my iPhone

Begin forwarded message:

> **From:** "Kupper, Kathy" <kathy_kupper@nps.gov>
> **Date:** June 7, 2019 at 6:26:53 AM MDT
> **To:** "Alley, Lauren" <lauren_alley@nps.gov>
> **Cc:** Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov>
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>
> Thanks Lauren!
>
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> National Park Service

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On Thu, Jun 6, 2019 at 8:08 PM Alley, Lauren <lauren_alley@nps.gov> wrote:

> Kathy/all,
>
> Please see below for some context. I'm copying USGS public affairs for the Northern Rockies (Sarah Beldin) and the lead USGS scientist (Dan Fagre) on this response in case you or DOI have any follow up questions for us.
>
> Cheers,
>
> Lauren
>
> The park works closely with the U.S. Geological Survey to understand glacial retreat and how it impacts the park ecosystem.
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> A paper published in 2003 predicted that the glaciers in Glacier National Park would be gone by 2030, based on modeling that the glaciers would continue to melt at the same rate that they had over the previous decades.
>
> Further research in the late 2000s revealed specific glaciers were melting even faster than the rate used in the 2003 model, which began predictions that at least some of the glaciers may be gone as early as 2020. (See page 80 of the linked article.)
>
> Research on the glaciers has continued. In the last several years, USGS has released peer reviewed research on glacial retreat that provide greater accuracy than was available early on in the research project, including improved satellite images and a greater understanding of how site specific conditions affect glacier size and melt rate. The research shows variability in the rate at which individual glaciers are melting though the overall declining trend continues. Recent data show reductions in size range from 9%-96%, averaging a 68% reduction in glacial area overall.
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> The park continually updates its interpretive material including exhibits based on the latest research available for multiple park resource topics. This winter, the park was able to fund an update to the St. Mary Visitor Center glacier exhibit to reflect the latest modeling.
>
> In the past three years, the park has used the following statement when responding to the multiple media requests it receives about glacial retreat:
>
> "There are currently 26 glaciers in the park. Scientific models project that many will no longer meet the size criteria used to define a glacier sometime between 2030 and 2080."

Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

On Thu, Jun 6, 2019 at 12:11 PM Kupper, Kathy <kathy_kupper@nps.gov> wrote:

> Hi Lauren,
>
> DOI received a media inquiry regarding the following article. Can you please let us know if the info in it is correct and/or any related background?
> https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc
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Conversation Contents

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Lauren Alley <lauren_alley@nps.gov>

From:	Lauren Alley <lauren_alley@nps.gov>
Sent:	Thu Jun 06 2019 13:13:47 GMT-0600 (MDT)
To:	tracy_ammerman@nps.gov
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

Tracy- do you have anything to add? Assume that we are updating interpretive material and have been for several years to reflect latest USGS models.

Sent from my iPhone

Begin forwarded message:

From: "Kupper, Kathy" <kathy_kupper@nps.gov>
Date: June 6, 2019 at 12:11:09 PM MDT
To: "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>
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Thank you,
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Public Affairs Specialist
Office of Communications
National Park Service
(202)513-7263
www.nps.gov

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"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Thu Jun 06 2019 13:31:46 GMT-0600 (MDT)
To:	Lauren Alley <lauren_alley@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Lauren,

Yes, we are indeed updating our interpretive information/exhibits based on emerging information from USGS. There was nothing covert or sneaky about it, but simply an effort to try to have more accurate information in place before the SMVC opened to the public this year. The park's position (based on scientific evidence) is still that our glaciers are shrinking and disappearing and that there is typically a net loss of mass "at the end of the year." The prediction that they would be gone by 2020 appears to have been an inaccurate estimate based on the models used at that time, but there is absolutely no disagreement in the scientific community that they will disappear in the not-too-distant future. GLAC is removing specific dates and using more general language, as we (and USGS) have realized that although the trend is evident, citing a specific date was perhaps presumptive.

I hope this helps. I am happy to chat with you more if you'd like. Of course, discussion with Dan Fagre and/or Caitlyn Florentine might be useful, as well.

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930

On Thu, Jun 6, 2019 at 1:13 PM Lauren Alley <lauren_alley@nps.gov> wrote:

Tracy- do you have anything to add? Assume that we are updating interpretive material and have been for several years to reflect latest USGS models.

Sent from my iPhone

Begin forwarded message:

From: "Kupper, Kathy" <kathy_kupper@nps.gov>
Date: June 6, 2019 at 12:11:09 PM MDT
To: "Alley, Lauren" <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April
~~~~~~~~~~~~~~~~~~~~~~~~

Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>
Subject: Media Inquiry: [EXTERNAL] Is this true?

Hi Lauren,

DOI received a media inquiry regarding the following article. Can you please let us know if the info in it is correct and/or any related background?
https://wattsupwiththat.com/2019/06/06/glacier-national-park-quietly-removes-its-gone-by-2020-signs/?fbclid=IwAR3axKgzLYeH6N2yllLux_VB4xEwGPksHqvGBIqfD16GB4hOPUtLa2ihllc

Thank you,
Kathy

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"Ammerman, Tracy" <tracy_ammerman@nps.gov>

From:	"Ammerman, Tracy" <tracy_ammerman@nps.gov>
Sent:	Thu Jun 06 2019 14:56:05 GMT-0600 (MDT)
To:	Daniel Lombardi <daniel_lombardi@nps.gov>
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

FYI

Tracy

~~~~~~~~~~~~~~~~~~~~~~~~~~
Tracy L. Ammerman
Chief of Interpretation and Education
Glacier National Park
406-888-7930
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From: **Ammerman, Tracy** <tracy_ammerman@nps.gov>
Date: Thu, Jun 6, 2019 at 1:31 PM
Subject: Re: Media Inquiry: [EXTERNAL] Is this true?
To: Lauren Alley <lauren_alley@nps.gov>

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"Alley, Lauren" <lauren_alley@nps.gov>

From:	"Alley, Lauren" <lauren_alley@nps.gov>
Sent:	Thu Jun 06 2019 15:50:08 GMT-0600 (MDT)
To:	Jeff Mow <jeff_mow@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, "Carolin, Tara" <tara_carolin@nps.gov>, "Sladek, Melissa" <melissa_sladek@nps.gov>, "Peitzsch, Erich" <epeitzsch@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Fwd: Media Inquiry: [EXTERNAL] Is this true?

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Management Assistant
Glacier National Park
406.888.5838

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To: Alley, Lauren <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>

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"Fagre, Daniel" <dan_fagre@usgs.gov>

From:	"Fagre, Daniel" <dan_fagre@usgs.gov>
Sent:	Thu Jun 06 2019 16:31:32 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
CC:	Jeff Mow <jeff_mow@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, "Carolin, Tara" <tara_carolin@nps.gov>, "Sladek, Melissa" <melissa_sladek@nps.gov>, "Peitzsch, Erich" <epeitzsch@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Hi Lauren,
Only one correction - "peer reviewed research on glacial retreat modeling" - we haven't done retreat modeling recently but have published papers on glacier retreat. Retreat modeling by other scientists on glaciers in Switzerland and Canada show similar time frames for glacier disappearance as your statement referencing 2030 to 2080 for GNP's glaciers.
Dan

On Thu, Jun 6, 2019 at 3:50 PM Alley, Lauren <lauren_alley@nps.gov> wrote:

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Lauren Alley
Management Assistant
Glacier National Park
406.888.5838

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From: **Kupper, Kathy** <kathy_kupper@nps.gov>
Date: Thu, Jun 6, 2019 at 12:11 PM
Subject: Media Inquiry: [EXTERNAL] Is this true?
To: Alley, Lauren <lauren_alley@nps.gov>, Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>

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****
Daniel B. Fagre, Ph.D.
USGS Northern Rocky Mountain Science Center
215 Mather Drive
Glacier National Park
West Glacier, MT 59936
Ph: 406-888-7922

Email: dan_fagre@usgs.gov
****

"Carolin, Tara" <tara_carolin@nps.gov>

From:	"Carolin, Tara" <tara_carolin@nps.gov>
Sent:	Thu Jun 06 2019 16:56:12 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>
CC:	Jeff Mow <jeff_mow@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, "Sladek, Melissa" <melissa_sladek@nps.gov>, "Peitzsch, Erich" <epeitzsch@usgs.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

A few additional points you might choose from include:

A paper published in 2003 predicted that the glaciers in Glacier National Park would be gone by 2030, based on modeling that the glaciers would continue to melt at the same rate that they had over the previous decades.

Further research in the late 2000s revealed specific glaciers were melting even faster than the rate used in the 2003 model, which began predictions that at least some of the glaciers may be gone as early as 2020. (See page 80 of the linked article.)

Research on the glaciers has continued, demonstrating variability in the rate at which individual glaciers are melting though the overall declining trend continues. Recent data show reductions in size range from 9%-96%, averaging a 68% reduction in glacial area overall.

Tara Carolin, Director
Crown of the Continent Research Learning Center
Glacier National Park
406-888-7863
406-888-7903 (fax)
https://www.nps.gov/rlc/crown

Research Learning Centers increase the effectiveness and communication of science in national parks.

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"Alley, Lauren" <lauren_alley@nps.gov>

From:	"Alley, Lauren" <lauren_alley@nps.gov>
Sent:	Thu Jun 06 2019 18:08:42 GMT-0600 (MDT)
To:	"Kupper, Kathy" <kathy_kupper@nps.gov>
CC:	Marco De Leon <marco_deleon@nps.gov>, Vanessa Lacayo <vanessa_lacayo@nps.gov>, April Slayton <april_slayton@nps.gov>, Jeremy Barnum <jeremy_barnum@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Daniel Fagre <dan_fagre@usgs.gov>, Jeff Mow <jeff_mow@nps.gov>
BCC:	tracy_ammerman@nps.gov
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Kathy/all,

Please see below for some context. I'm copying USGS public affairs for the Northern Rockies (Sarah Beldin) and the lead USGS scientist (Dan Fagre) on this response in case you or DOI have any follow up questions for us.

Cheers,

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Sent:	Fri Jun 07 2019 13:54:05 GMT-0600 (MDT)
To:	"Alley, Lauren" <lauren_alley@nps.gov>, Tracy Ammerman <tracy_ammerman@nps.gov>, "Mow, Jeff" <jeff_mow@nps.gov>, Daniel Fagre <dan_fagre@usgs.gov>, erich peitzsch <epeitzsch@usgs.gov>, Melissa Sladek <melissa_sladek@nps.gov>, "Beldin, Sarah" <sbeldin@usgs.gov>, Teagan Tomlin <teagan_tomlin@nps.gov>, Bill Hayden <Bill_Hayden@nps.gov>
Subject:	Re: Media Inquiry: [EXTERNAL] Is this true?

Teagan at the front desk is getting numerous angry calls (yelling and violent swearing) over this article today. She contacted our office since almost all of you are out today. I forwarded her Lauren's email with information she can use and and also told her she could just take names for later response.

We may need to develop a more proactive response...

Tara Carolin, Director
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