Alaska Park Science

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Alaska Regional Office
Anchorage, Alaska

Scientific Studies on Climate Change in Alaska's National Parks

Volume 6, Issue 1

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Cover: Icebergs slosh around the remnants of glacier-dammed Iceberg Lake just after catastrophic failure of the ice dam. Article page 30. Photograph by Michael Loso.

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Photograph by Mike Booth

Author Michael Loso stands under a gigantic iceberg stranded by the sudden drainage of Iceberg Lake. The former inlet stream passes by in the foreground. Read the story on page 30.

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Climate Change and the International Polar Year

Author Bob Winfree investigates a glacier drain channel.

As we produce this, our tenth issue of *Alaska Park Science,* we are also preparing for the start of the International Polar Year (IPY), 2007-2009. The IPY is the fourth, since 1882, in a series of grand international explorations of the earth's Polar Regions. I remember the last such event, the International Geophysical Year (IGY), in 1957-1958, as a time of great discoveries and excitement. Despite Cold War tensions, thousands of scientists from across the globe jointly explored the physical structure and workings of the earths crust, oceans, polar ice caps, and atmosphere. The world's first orbiting satellites were launched during IGY, the Antarctic ice cap was measured, and the theory of continental drift was confirmed. With these scientific and technical achievements also came major accomplishments in international conservation, cooperation and peace. By the close of 1959, twelve nations had signed an Antarctic Treaty, declared that Antarctica would be used only for peaceful purposes, and committed to the continuation of scientific cooperation.

Today, 50 years from the start of the IGY, scientists from many nations have joined together again to better understand the earth's Polar Regions and to share what they learn with others. To mark the start of IPY, the National Park Service has focused this issue of the *Alaska Park Science* journal on the subject of climate change in Alaska's national parks. Our authors explore the subject from several locations, time frames, and perspectives. Alaska has certainly experienced climate change before. This is, after all, the place through which humans successfully migrated to North America some 12-15,000 years ago during the height of the last major "Ice Age." If current trends continue, and if future projections hold true, the ecological and societal effects of climate change will be considerable in the twenty-first century.

Climate change is one of the foremost issues of concern listed in the new NPS

Alaska has certainly experienced climate change before. ... If current trends continue, and if future projections hold true, the ecological and societal effects of climate change will be considerable in the twenty-first century.

National Park Service photograph by Ron Karpilo

Alaska Region Science Strategy, which states that "Climate change is changing habitats, use of areas, accessibility, biotic communities, diseases and causing other effects that will change the characteristics of parks as well as the type of management actions required to maintain parks values and mission." More science, more integration and more use of the information will be critical for understanding and dealing with change. During IPY, a broad suite of arctic and climate change related projects will be underway in and around the national parks in Alaska. The NPS Arctic and Central Alaska Inventory and Monitoring Networks will implement "vital sign" monitoring on a broad suite of biological, chemical and physical indicators of ecosystem health across more than 40 million acres of NPS lands and waters in Alaska. The Southwest and Southeast networks will design and test vital sign monitoring protocols for another 15 million acres. The NPS Shared Beringian Heritage (Beringia) program will support local and international participation in cooperative research, scholarship, and cultural exchanges intended to understand and preserve natural resources and protected lands, and to sustain the cultural vitality of Native peoples in the Central Beringia region. Then, in October 2008, we will invite scientists, scholars, park managers, educators and others interested in parks and protected areas in greater Beringia to Fairbanks, Alaska, for a symposium—Park Science in the Arctic. Throughout and after IPY, scientists from the NPS, other agencies, universities, and institutions will undertake scientific and scholarly studies to more fully understand the biological, physical, cultural and social sciences and history of the national park units in Alaska. We look forward to providing information from many of these studies in future issues of *Alaska Park Science*.

Robert A. Winfree, Ph.D.
Alaska Regional Science Advisor

For More Information:

International Polar Year:
http://www.ipy.org/about/what-is-ipy.htm

Alaska Region Science Strategy:
http://165.83.62.205/General/AK2Day/2006ScienceStrategy.doc

Beringia:
http://www.nps.gov/akso/beringia/

Inventory and Monitoring in Alaska:
http://www.nature.nps.gov/im/units/AKRO/index.htm

“Arrange for Change” Interpreting the Science of Climate Change in National Parks

By John Morris

Two years ago, an education institute was convened by the National Aeronautic and Space Administration (NASA) that sought to blend the science of NASA with the communication expertise of the National Park Service. The Earth to Sky program drew together scientists and interpreters from both agencies to collaborate on specific interpretive products for use in the parks. Climate change was one of the first topics identified to benefit from the wealth of NASA scientific resources.

(Above) The “Blue Marble”: Using a collection of observations, a seamless, true-color mosaic of our planet.

NASA Goddard Space Flight Center image

(Left) Wildland fire in Denali National Park and Preserve in 2005.

National Park Service photograph

When queried last year, few of Alaska parks addressed climate change in their formal programs, although most received questions about it from visitors. However, the parks do promote themes that address change as a part of their stories. Evidence for climate change is more obvious in the arctic than almost anywhere else on the planet. Given that, and the reality that we hear more and more about it every day in the media, discussing climate change will have universal appeal for our audiences. It seems inevitable that in the very near future, interpreters and resource specialists alike will need to respond to these questions about global climate change and its implications.

Informal interpretation can be challenging. Unlike formal programs, the visitor is in control of where an individual contact goes. Interpreters need to be prepared with a wealth of specific knowledge and be able to think fast, changing the content of their discussion as needed. With this challenge in mind, the Earth to Sky workgroup developed an interactive tool to help rangers prepare for these informal conversations. A database of potential responses for front-line supervisors and rangers was designed, providing a broad scientific background about climate change as well as practical applications for discussions with visitors. In addition, a traveling display and general “Climate Change in National Parks” brochure were developed. These can be borrowed by parks everywhere and used as catalysts for informal conversations. The science of changing climate is ready to be communicated, in ways visitors will understand and appreciate.

Climate Change is Happening

Warmer winters and longer, more intense melt seasons have increased the rate of glacial retreat in most of Alaska national parks *(OASLC 2005)*. Higher temperatures and changes to precipitation, especially during winter, have brought high mortality to the black spruce, in particular, by expanding infestations of bark beetles and carrying them to new ranges. Increasing sea level and the loss of sea ice has increased erosion in many coastal areas and is damaging structures and may threaten the loss of archeological sites *(USGS 2002)*. For years, parks have witnessed an increase in the frequency and duration of wildland fires. Recent studies have concluded that a changing climate, not previous fire-suppression policies or land-use changes, seems to be the major cause *(Westerling et al. 2006)*.

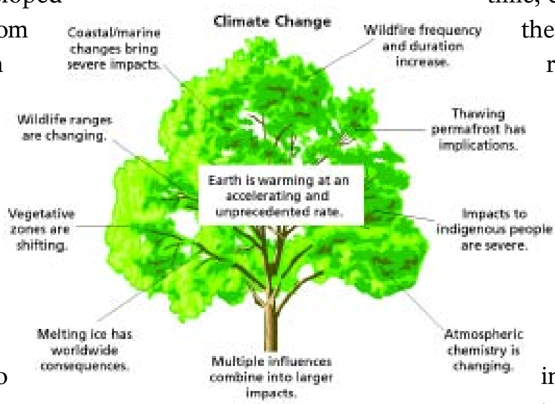
While many changes to park resources are inevitable, they can still influence the ways in which visitors use and enjoy the parks. Park closures are resulting from increased wildfires. Rising winter temperatures and reduced snow pack have halved the length of time each year in which arctic travel is feasible *(ACIA 2004)*. Salmon and trout populations, popular for fishing, are showing high mortality rates due to warming water and flooding *(EPA 1999, O'Neal 2002)*. Indigenous users of these fisheries are at risk to lose not only a food source, but a way of life. Many of these impacts have economic implications.

What the Science Tells Us

Scientists who study climate change agree that human activities are a big part of the current warming trend. As stated in the 2007 report of the Intergovernmental Panel on Climate Change, "Most of the observed increase in globally averaged temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" *(IPCC 2007)*. At Mauna Loa in Hawaii and around the world, specific evidence has been gathered of an increase in greenhouse gases in the atmosphere, predominantly carbon dioxide, which is contributing to the warming of the planet *(Keeling 1978)*. CO_2 levels in the atmosphere today are higher than they have been in over 650,000 years *(RealClimate 2005)*. For our national parks to thrive and for us to continue enjoying them, it seems appropriate now to do what we can to reduce climate change impacts and adapt to their consequences. NASA scientists remind us that fortunately, we now have the tools, knowledge, and ingenuity to better understand these changes and make informed choices for coping with them. They tell us that our own survival may be at stake *(Hansen 2006)*.

A Tool for Communicating About Climate Science

Efforts are now underway to educate park visitors about many of these changes. For the last year, rangers throughout Alaska have been asked to keep track of the specific questions already being asked about climate change by visitors at their sites. A range of possible responses was developed for each question, from basic orientation to more in-depth information, to responses that might facilitate an educational experience for the visitor. Once defined, responses were sorted into categories and annotated with specific source materials and multiple examples of appropriate techniques to use. Categories were based on the key findings of the Arctic Climate Impact Assessment *(2004)*.



A Climate Change Decision Tree.

The Decision Tree

Imagine climate change as a tree, each of its branches representing an implication of changing climate, and each of the leaves on the branches representing the questions visitors are asking about it. Here's an example of how these multiple responses work for one question:

Are These Changes Just the Result of Natural Variability?

Basic response: Current research reflects a scientific consensus that the climate changes experienced today cannot be attributed to natural variability alone *(ACIA, IPCC)*. In the past 125 years, the average temperature of the planet has begun to rise and the increase is accelerating. At the same time, carbon dioxide in the atmosphere has risen to its highest concentrations in more than 650,000 years, with its rise also accelerating. Scientists suspect this may be interfering with the Earth's natural balancing that has occurred prior to now.

In-Depth response: It is important to understand that at many times in Earth's geologic history, there have been cooler and warmer periods than at present. Besides human activities, variations are due to large scale global influences such as volcanism and meteor impacts. These charts help provide a fundamental understanding of Earth's paleo-history of recent times.

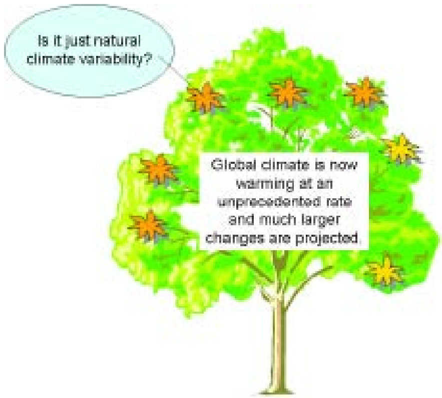
As the ranger illustrates and explains these charts, opportunities should arise for the visitor to gain new perspectives and perhaps, feel amazement at the long-term records we have for climate on Earth.

Interpretive response: After covering the charts about paleo-history, the interpreter could ask the visitor what they imagine might have caused the abrupt changes found to exist in those records. What are some possible catalysts? The intent for this response is to help them discover for themselves how changes in the atmosphere might create big impacts. Ultimately, the discussion should try to inspire them to wonder what could be done to solve the CO_2 problem and adapt.

Here's how

First, an experiment *(Bindschadler 2005):* (the interpreter can do it or suggest it—whichever is most appropriate)

Take an ice cube and place it on a table at room temperature. If its temperature is measured before and after the ice cube melts, notice it stays the same, 32°F (0°C). Even though a lot of energy is needed to convert the ice to a liquid, the temperature does not change. Consequently, the energy needed to melt ice can be easily overlooked. If you heat the same quantity of water, applying the same amount of energy, its temperature would rise to 176°F (80°C). The point of this experiment is this: Ice near its melting point may be at a "tipping point"—a threshold where a lot of energy is going into the system, and the effects are not apparent until a critical level is reached. Once crossed, they are difficult to reverse. Is it possible that a similar tipping point



The Model – Question and Responses.

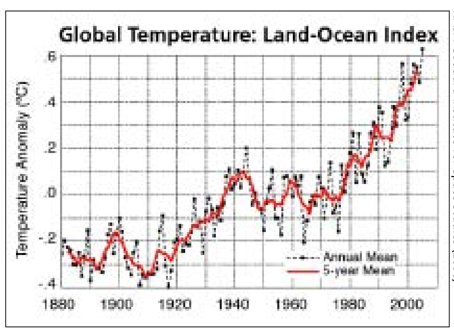
may be approaching for Earth?

Next, ask visitors if there is anything affecting the parks that might provide a clue as to why and when these tipping points might occur? What about the sun? In the early twentieth century, a Yugoslavian astronomer and mathematician provided an answer to what causes ice ages. Milutin Milankovitch recognized that minor changes in Earth's orbit around the sun and in the tilt of Earth's axis causes slight but important variations in the amount of solar energy that reaches any given latitude on the earth's surface. By reconstructing and dating the history of climatic variations over hundreds of thousands of years, scientists have shown that fluctuations of climate on glacial-interglacial time scales match the predictable cyclic changes in Earth's orbit and axial tilt. This persuasive evidence supports the theory that these astronomical factors control the timing of glacial-interglacial cycles.

Finally, ask the visitor what comprises air? Explain that greenhouse gases like CO_2 make up only about 1% of the atmosphere, so what would be the logical consequence of pouring lots more CO_2 in the atmosphere? Illustrate for them the modeling data from the IPCC, reflecting how anthropogenic and natural variability are needed to produce the warming effects being observed today.

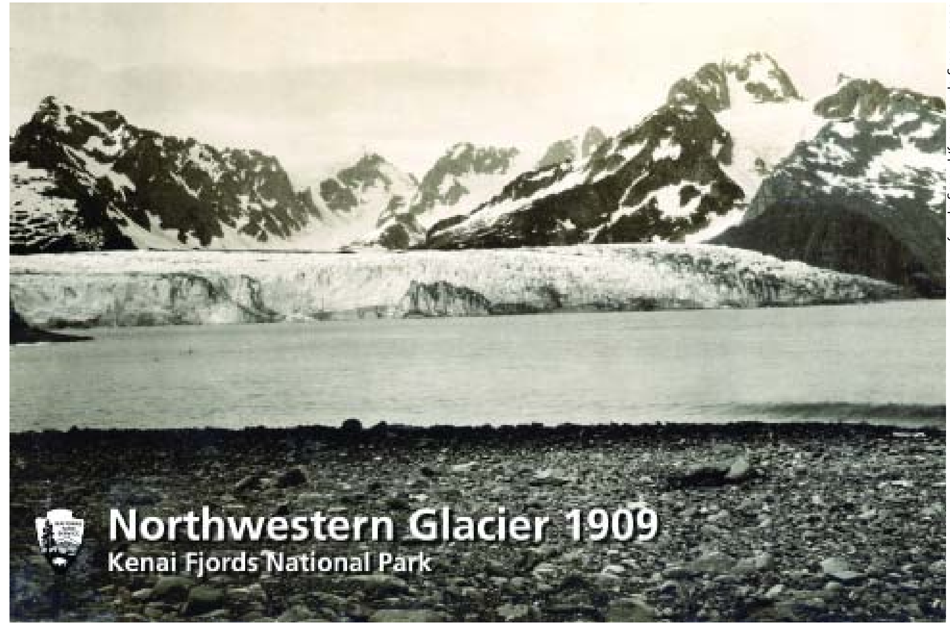
A Compelling Message of Hope

National parks are responding to these changes. Glacier Bay recently hosted a "Climate Friendly Parks" workshop, co-sponsored by the Environmental Protection Agency, to evaluate energy use and identify efficiencies to improve park operations. Other parks are developing solar and wind energy, fuel cells, electric and hybrid forms of transportation, and mass transportation where high visitation exists. Vulnerable resources are being monitored in many Alaska parks and several have researchers who are specifically addressing climate change impacts. With the development of this training tool, rangers in many parks are

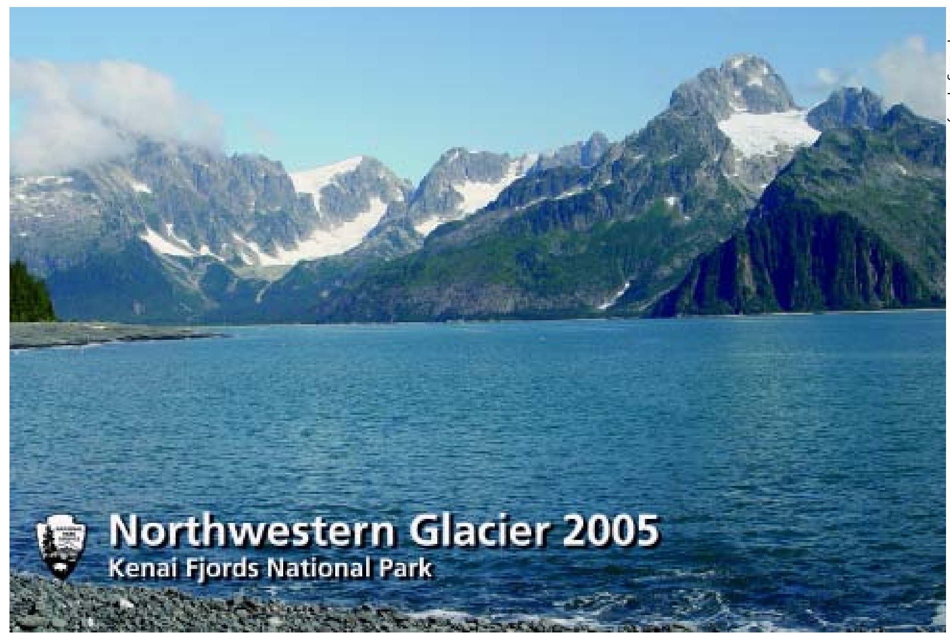


NASA Goddard Institute for Space Studies (2006)

A line plot of global annual-mean surface air temperatures derived from the meteorological station network.

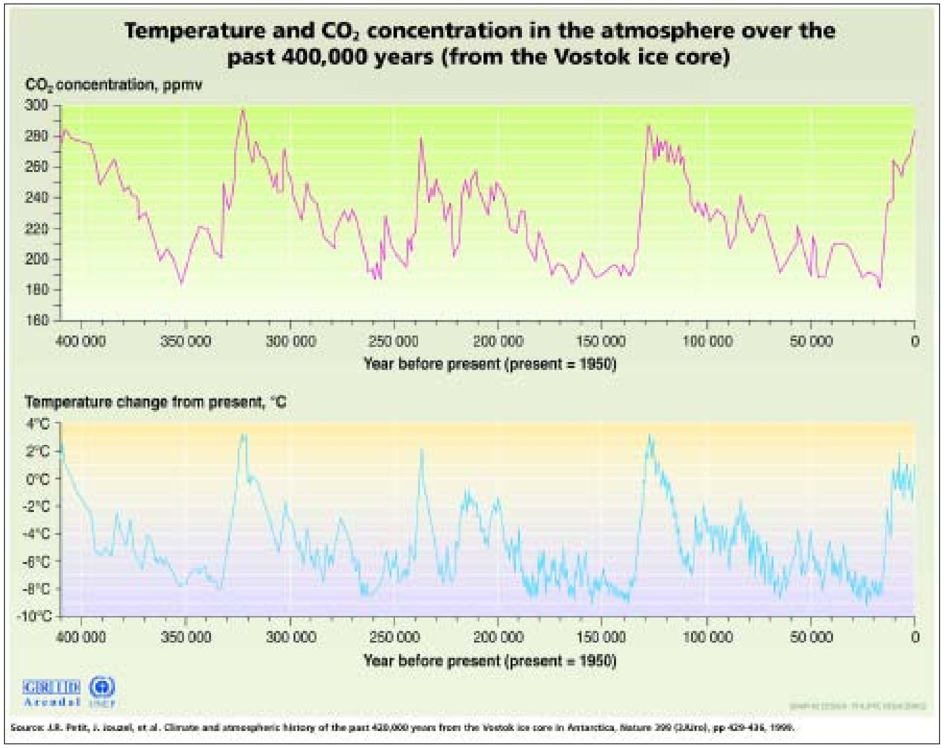


USGS Photographic Library, photograph by U.S. Grant



USGS photograph by Bruce F. Molnia

Glaciers are melting—Could it be that a "tipping point" is approaching for Earth?

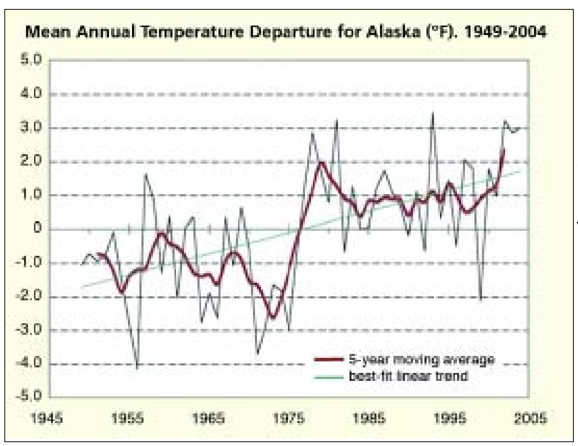


Temperature and CO_2 concentration in the atmosphere over the past 400,000 years. In UNEP/GRID-Arendal Maps and Graphics Library. Retrieved December 16, 2006 from http://maps.grida.no/go/graphic/temperature_and_co2_concentration_in_the_atmosphere_over_the_past_400_000_years.

being prepared with the latest information about climate science in order to answer questions and assist visitors in understanding climate change and its implications. Their message can be one of hope.

Two scientists at Princeton published a paper describing how we already possess the technologies needed to reduce the abundance of CO_2 and outlining strategies to do so within 50 years *(Pacala and Socolow 2004)*. Many of their suggestions involve choices that individuals can make to conserve and reduce energy use. Changing to energy efficient light bulbs and appliances, unplugging computers and electronic devices when they’re not in use, and using public transportation are good examples of conservation practices. There are many more.

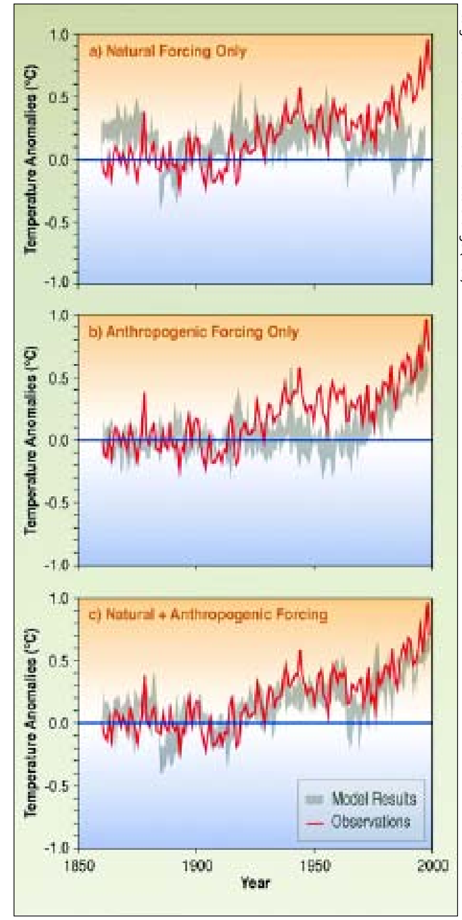
Many times during our nation’s history, citizens have confronted difficult circumstances and found creative solutions. Our national parks tell compelling stories about the American Revolution, the abolition of slavery, the fight for civil rights, and about countless inspirational personalities who have made a difference for our nation. Many parks even convey stories about people’s responses over thousands of years to shifting climate patterns. These stories are now part of a call to action for all visitors in the stewardship of our resources for future generations. Rangers can emphasize the importance of all participating in answer-



AK Climate Research Center, University of Alaska Fairbanks

Thomas Jefferson once said “To possess facts is knowledge, to use facts wisdom, to choose facts education.” The challenge of good interpretation is in choosing and creating compelling opportunities for visitors to make their own connections with the significance of park resources. If successful, interpreters facilitate memorable experiences that inspire new insights about the resources and evoke appreciation for the meanings they represent.

(Left) The red line shows 5-yr mean annual temperatures for the past 50 years in Alaska.



Intergovernmental Panel on Climate Change (IPCC)

The red line indicates how actual temperature observations compare to modeled temperature results for natural and human caused influences on global climate.

ing that call.

Regardless of the causes, taking action to manage the impacts of changing climate will have positive benefits for our resources. Parks are places where people learn what it means to be a responsible citizen and steward of community resources. In the future, national parks may tell the story of our collective success in dealing with climate change. What more compelling message is there for national parks to promote?

Here are a few basic websites of particular interest to climate change:

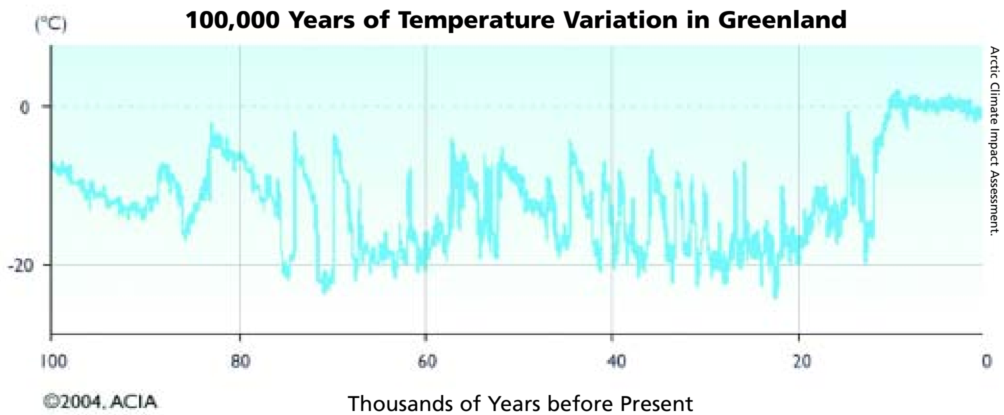
The Intergovernmental Panel on Climate Change
http://www.ipcc.ch/

The Arctic Climate Impact Assessment
http://amap.no/acia/ACIAContent.html

Understanding and Responding to Climate Change
http://dels.nas.edu/basc/Climate-HIGH.pdf

EPA's Global Warming—Actions
http://yosemite.epa.gov/oar/globalwarming.nsf/content/ActionsIndividualMakeaDifference.html

NPS/NASA Earth-to-Sky Interpretive Training tool on Global Climate Change
http://www.earthtosky.org



100,000 years of temperature variation based on ice-core analysis in Greenland.

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Science 313 (5789): 940-943.

Melting Denali: Effects of Climate Change on the Glaciers of Denali National Park and Preserve

By Guy W. Adema, Ronald D. Karpilo, Jr., and Bruce F. Molnia

National Park Service photograph

An NPS researcher recreates a panorama of the Muldrow Glacier at Oastler Pass.

Figure 1. (Upper Left) S.R. Capps of the U.S. Geological Survey first photographed the Hidden Creek Glacier in 1916 (just east of the Kahiltna Glacier). (Lower Left) The change is particularly apparent due to the granite bedrock in this 2004 photograph.

Upper photograph: U.S. Geological Survey photograph
Lower photograph: National Park Service photograph

Introduction

Climate and topography are the primary drivers of glacial systems, and glaciers record the trends for all to observe. The climate is constantly changing, and glaciers have responded through time, with evidence of advance and retreat cycles recorded in the geologic record. The growing evidence of unprecedented warming rates and wide ranging effects is well documented, recently in the comprehensive and international Arctic Climate Impact Assessment *(2005)*. There are substantial and far reaching impacts of a warming climate, but few are as dramatic and visible to national park visitors as changes to glacial systems.

Glaciers are a significant geologic feature of Denali National Park and Preserve, currently covering approximately 17 percent or 1,563 square miles (4,047 km^2) of the park. Highly sensitive to changes in temperature and precipitation, glaciers dynamically react to climatic drivers by thickening and advancing during periods of increased accumulation, and thinning and retreating during periods of increased ablation. Alteration of the Denali cryosphere directly influences the physical landscape, the local hydrologic regime, and the diversity and spatial distribution of biologic communities in the park. Understanding the scale and pace of past glacial system changes in Denali provides critical insight into how these processes may continue in the future.

Glacier monitoring in Denali has taken various forms since the early 1900s, with early explorers, visitors, and managers documenting the landscape through photography or descriptive field notes, to more recent mass balance monitoring and detailed measurement of change in glacial extent through formal surveys and satellite imagery. The composite data presented herein characterize the ongoing change in Denali and tell a compelling story of glacial retreat, dramatically illustrated through comparative photography and supported by detailed measurements.

Worth a Thousand Words

Like many of today's visitors, early explorers, visitors, and managers approached Denali with an appreciation for natural systems. Their excitement for the newfound places enticed them to record what they saw to share with the rest of the world, whom they (as we) might often feel, were not as fortunate to view firsthand. Our studies of glacial change in Denali have benefited tremendously from the careful records of early visitors. We are able to visually identify 50-80 years of

Figure 2. The Kahiltna Glacier appears largely unchanged, but close inspection shows significant lowering of the surface and stabilization of marginal scour zones. The alpine glaciers flanking the east facing ridge have diminished considerably.

Figure 3. The view from this established photo-point near Eielson Visitor Center is changing considerably. The ridgeline in the left (south) side of the historic photo is nearly covered with alpine glaciers, while today only a few small pockets of ice remain. Careful inspection also shows considerable thinning of Sunset Glacier (valley glacier on left).

glacial change across the park through comparative photography.

Data gathering and research involved locating and digitizing historical photographs (taken circa 1906-1950) from the USGS Photo Archive in Denver, Colorado, the Denali National Park and Preserve archive, and the University of Alaska at Fairbanks archives and library. Photo quality ranged from highly degraded black and white and sepia 'snapshot' size photographs to professional quality 8"x10" photo negatives taken by Bradford Washburn. Significant contributions came from the collections of Cathcart, Reed, Washburn, and Capps. We are continually in pursuit of early photographs documenting glaciation in Denali—building a comprehensive record of change.

Modern photographs, repeating historical photographs as accurately as possible, were taken in both digital and negative film formats. A Nikon D100 digital SLR camera and a Nikon F100 film camera with Fuji Velvia and Provia films with a variety of lenses were used for this study. We hiked to the photograph sites to minimize potential impacts and conflicts whenever possible, using motorized access only where necessary.

Data suggest that the majority of the glaciers included in this study have generally retreated, thinned, or stagnated over the observed time periods. The most notable change has been on glaciers with accumulation zones below 8,200 ft (2,500 m). On the East Fork Teklanika Glacier there has been nearly ~980 ft (300 m) of obvious thinning and associated retreat. In addition to observed changes on the larger glaciers, small, "pocket" glaciers have undergone significant thinning and retreat. There has been surge activity in the past century, but no glaciers show signs of thickening or advance.

Figures 1-6 demonstrate the considerable perspective that can be gained from studying historical photographs. General changes in glacier thickness, terminus extent, ice dynamics, and elevational variations can be interpreted. Inferences of ecological changes and impacts to the dependent hydrologic regime are logical applications of the data.

Ground Truthing Change

While comparative photography provides extensive data that tell a powerful story, it lacks quantitative rigor that is often preferred when developing scientific conclusions. In order to accurately measure the change, park personnel regularly survey glacier terminus positions of the more accessible glaciers. Earlier surveys used traditional theodolite surveying techniques while

Figure 4. The Sunset Glacier is close to the heavily visited Eielson Visitor Center and viewed by many of the 400,000 park visitors each year.

Figure 5. The glacier at the head of the east fork of the Teklanika River has lost approximately 980 ft (300 m) of thickness and experienced significant associated retreat.

Figure 6. This panorama of the Muldrow Glacier, taken from Oastler Pass, shows the loss of hanging glaciers on Mt. Brooks (center).

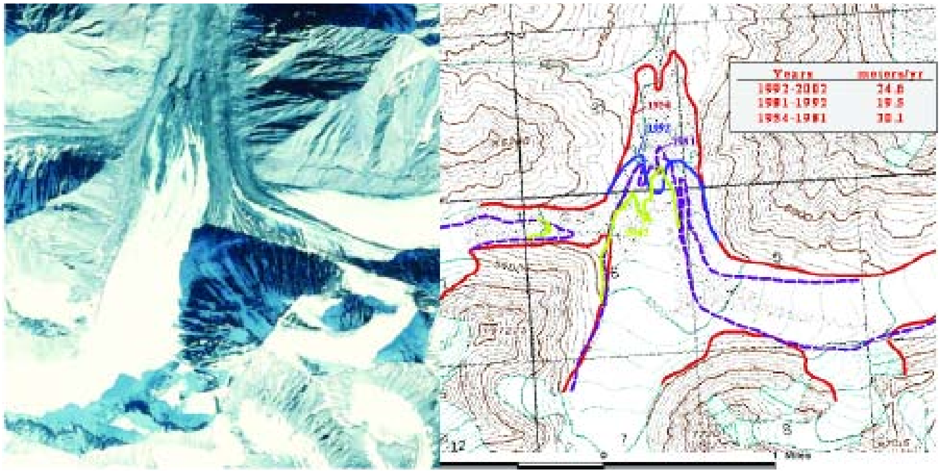


Figure 7. Detailed field surveys document glacier retreat, with average rates of approximately 66 ft (20 m) per year since the 1950s.

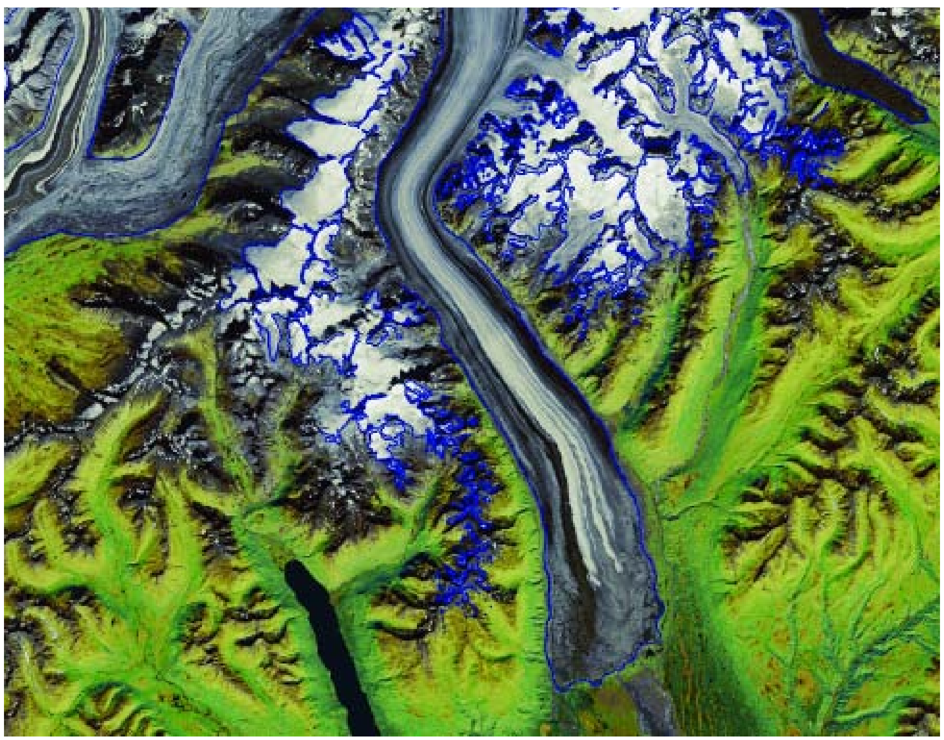


Figure 8. Glacial extent is digitized from aerial photography and satellite imagery to document change, a 2001 Landsat scene of the Kahiltna Glacier terminus area is shown here.

map-grade GPS measurements are now the standard. Measurements indicate retreat on all measured glaciers, with averages near 66 ft (20 m) per year. *Figure 7* is an example of the results on the Middle Fork Toklat Glacier. GPS survey results are compared to aerial photography and satellite images to document the change in the terminus position.

Measuring the positions of the termini in the Alaska Range is complicated by the geology of the park. Many of the best known coastal Alaska glaciers occur on geology dominated by fairly durable metamorphic and igneous rocks. In contrast, while the Mt. McKinley massif has a granite core, many of the glaciers occur in highly friable marine sedimentary rocks. These rocks quickly break down and form large medial and lateral moraines which often disperse to veil the glacier termini, providing insulation which slows retreat. While glacial extent is an important part of the glacial system, volume change measurements provide a more robust estimate of glacial health.

Volume change calculations require significantly more data and a spatial analysis of glaciers. Arendt et al. *(2002)* methodically estimated volume change of Alaska glaciers using laser altimetry measurements taken from a low flying plane. Measurements suggested that many of Denali's glaciers were losing up to 6.6 ft (2 m) of vertical water equivalency per year. They showed that the widespread loss of the volume in Alaska glaciers contributes substantially to sea level rise. Detailed ongoing work on volume loss will help discriminate elevational variations in volume change. Park scientists are currently using LIDAR (laser altimetry of entire surfaces) to calculate volume change on the Muldrow Glacier.

Another method used to quantify glacier change is through radar depth measurements, repeated in the same location over a time interval. Shown in *Figure 9,* the Muldrow Glacier is observed to thin by approximately 66 ft (20 m) between 1979 and 2004.

Mass balance trends also provide important insight to the behavior of glacial systems. Mass balance index sites, described by Mayo *(2001)* and Adema (in press), provide single point quantified trends of glacier dynamics. *Figure 10* shows the character of the Traleika index site near the 6,890 ft (2,100 m) elevation level. Measurements at this site are made at the end of the accumulation season (May) and the end of the ablation season (September). At this site, the Traleika glacier is observed to be thickening (increasing surface elevation) while having a negative mass balance. This might be explained through a process of the Traleika Glacier "building up", or "inflating." New ice is added to the glacier from higher tributaries and accumulation areas, while outflow is impeded by the downstream Muldrow and Brooks glaciers, causing a compressive flow regime. Concurrently, the glacier surface is experiencing more summer melting than winter accumulation (negative balance). The thickening caused by the compressive flow is greater than the negative surface mass balance, where more ice is melting than is accumulated each year. This phenomenon may contribute to the surge behavior of the Muldrow Glacier.

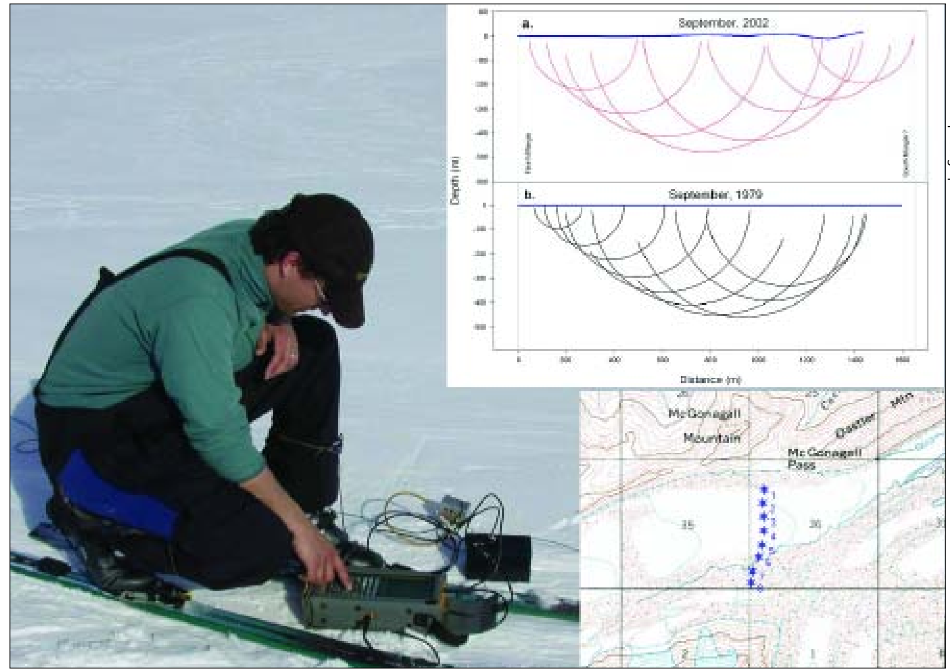
The Constant is Change

Glacial systems are inherently dynamic, defined by topography, accumulation rates, ice dynamics, and ablation rates. The warming climate's effect on glaciers is well documented through the re-creation of historic photos, field measurements, and interpretation of remotely sensed imagery. Glaciers are a key component of the hydrologic system, and as the glacial volumes and discharge change, so too will stream dynamics and sedimentation characteristics. The ecosystems will slowly evolve in reaction to the environmental changes ultimately caused by climatic forces. The rates of change documented are significant, and if the trends continue, the next generation will visit a very different Denali National Park and Preserve. Continued monitoring will provide objective documentation of our changing environment for future generations to better understand the complex ecosystem dynamics. Understanding the scale and pace of past glacial system changes in Denali provides critical insight into how these processes may continue in the future.

It is clear from this work that the glaciers of the central Alaska Range are thinning and retreating rapidly. More work is needed to model the inter-relationships of climate change and glacier fluctuations, but it appears that if current climatic trends continue, the glaciers of Denali National Park and Preserve will experience continued retreat.

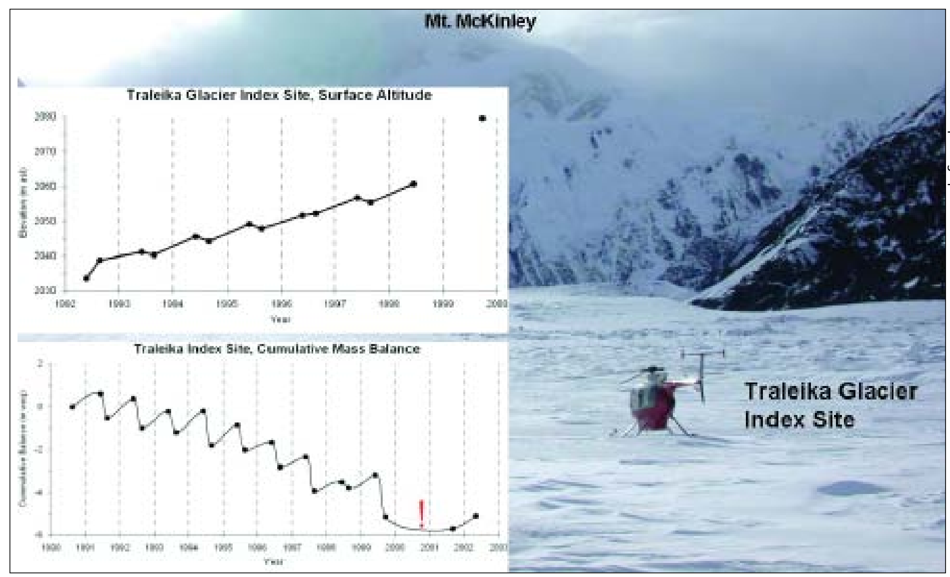
Acknowledgments

This work was made possible by the NPS Fee Demonstration program and the Central Alaska Inventory and Monitoring Network. Larry Mayo, Keith Echelmeyer, Phil Brease, Jamie Rousch, Chad Hults, Pamela Sousanes, and Adam Bucki played critical roles in the success of the glacier monitoring program.



National Park Service photograph

Figure 9. Ice radar measurements, repeated in the same location as historical measurements, help quantify the rate of glacial thinning.



National Park Service photograph

Figure 10. The surface mass balance of the Traleika glacier is negative while the surface elevation is rising, giving important clues to the overall glacial system operation.

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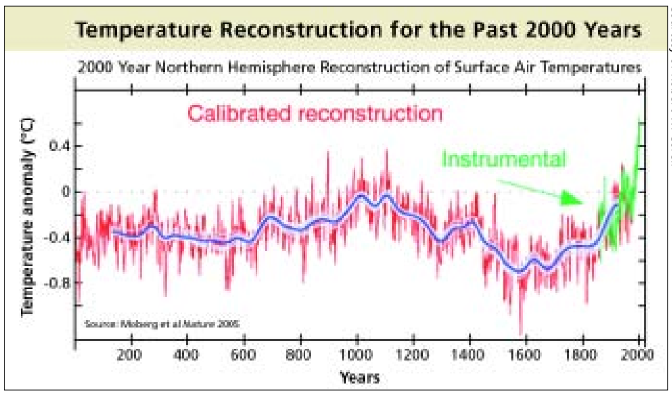
A Changing Climate: Consequences for Subsistence Communities

By Don Callaway

Evidence of rapid climate change is extensive throughout the arctic region and is posing substantial problems for subsistence users in Alaska. Increasing mean temperatures, increasing levels of carbon dioxide (CO_2) in the atmosphere, melting permafrost, changing habitat as the boreal forest moves north and a dramatic retrenchment in sea ice coverage all have enormous impacts on subsistence resources, which in turn have had many detrimental outcomes for subsistence harvesters.



Courtesy of Robert W. Corell

Figure 2. Alaska and Western Canada, the average winter temperatures have increased by as much as 3° to 4°C over the past 60 years, which is a significant increase given that the global increase over the past 100 years has been only about 0.6° ± 0.2°C.

Figure 1. (Left) Barrow hunter Carl Kippi with two ringed seals that he has harvested.

Photograph courtesy of North Slope Borough, Department of Wildlife Management

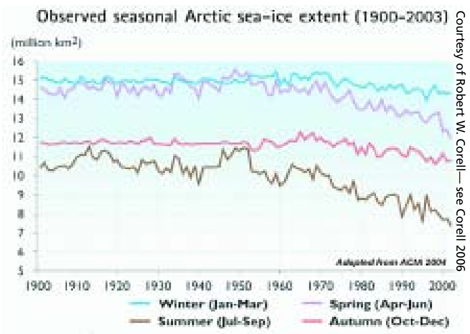
Temperature

For Alaska and western Canada, the average mean winter surface air temperature has increased by as much as 5° to 7°F (3° to 4°C) over the last 60 years *(Figure 2)*, which is, as the literature predicted, about triple the change experienced at the equator. This large observed warming trend has been accompanied by increased in precipitation of roughly 30% between 1968 and the 1990s.

Changing Habitat—Land

Boreal forests are expanding north at the rate of 62 mi (100 km) for every increase of 1.8°F (1°C) in air temperature. Predictions are that in the next 100 years the Seward Peninsula will have a transition from a primarily tundra ecosystem to one of white spruce and deciduous forest. Certain important subsistence species, like caribou, will likely disappear during this transition. For caribou herds in the state as a whole, caribou population dynamics may reflect non-linear dynamic systems and, as such, are difficult to predict given that slight changes in initial conditions can have profound outcomes as they are iterated throughout the system. Current analysis of the impacts of climate change on caribou populations covers the entire gamut of impacts. Some analysts see increased precipitation creating icy crusts on the snow during the winter, making “cratering”, caribou efforts to remove snow to access calorie rich mosses and lichens, taking a couple of hours rather than a few minutes. These energy expenditures will dramatically increase probability of winter starvation and high calf mortality. Decreased spring body fat of females will significantly reduce lactation and therefore calf survival rates. There are also concerns that longer and hotter summers will increase insect harassment on the calving grounds *(Gunn et al. 1998)*.

In contrast, Brad Griffith’s research on the Porcupine Caribou herd seems to indicate warmer temperatures lead to an earlier green-up on calving grounds *(Griffith et al. 2002)*. Quicker growth of vegetation provides increased nutrition for cows and increased milk production for the young. Half of all caribou deaths are from calves that die in June, but these habitat changes have increased overall survival rates. Griffith is aware of the downside of increased snowfall and rain in winter and is now trying to incorporate both factors in his



Courtesy of Robert W. Corell— see Corell 2006

Figure 3.

model. Compounding the difficulty of these estimates is the fact that increased spring precipitation makes it more difficult for caribou to migrate, with dramatic increases in calf mortality as they forge swollen rivers.

For forests in general the increased warming trend has brought about a 20% increase in growing days. However, there are also contrary indicators of increased pest disruption and fire frequency with some models indicating a 200% increase in total burn area per decade. All these factors impact habitat which in turn impact the distribution, density and availability of subsistence resources.

Sea Ice

Arctic summer (July-September) sea ice has decreased from about 4.5 million mi^2 (11.8 million km^2) in 1900 to an area of about 2.8 million mi^2 (7.3 million km^2) in 2004 *(Figure 3)*. This contraction represents about a 40% decrease in sea ice surface area. The sea ice provides habitat for seals, for polar bears that prey on the seals and for subsistence hunters which harvest both resource categories. During the summer, the ice edge is a particularly rich environment with nutrient mixture in the water column providing subsistence and florescence for the whole food chain from phytoplankton to fish, to seals, walrus, whales and human hunters. The decreasing sea ice truncates the available ice margin, which in turn decreases the rich habitat lowering the populations of the complex chain of species that depend on that habitat, e.g. walrus. Other deleterious outcomes include:

In 1998 a spring break up in the Beaufort Sea that was approximately three weeks early interrupted the ringed seal mother-pup nursing period. Ringed seals depend on the stable ice for their lairs and for a successful nursing period (typically six weeks). Wasted, skinny and stunted seal pups were found, by scientists and seal hunters. It is unclear the long term affects on ringed seal population, but interpolation indicates a decreasing population.

This will have a direct impact on polar bears, where ringed seals are an important part of their diet—a three year decline in ring seal productivity in the 1970s was reflected in poor condition and lower productivity in polar bears. In addition, recent surveys indicate polar bears having to swim much further in the fall to reach the polar ice cap, which is their most productive hunting habitat. Some have drowned in transit (perhaps due to rough seas) but almost all arrive with decreased and stressed energy budgets. Decreasing ring seal populations will also directly impact Iñupiat hunters who harvest ringed seal in substantial quantities.

Early spring breakup due to climate change and reduced sea ice area *(Figure 5)* has other direct consequences for Iñupiat marine mammal hunters. A recent study of whaling captains on the North Slope of Alaska indicates: whales arrive earlier, leads are wider, whales are further out, first year shore ice is brittle and difficult to find haul outs to process whales, new base camp locations must be found because of changing ice conditions, more dangerous open and rougher water, more boats are needed for safety reasons, bigger more expensive motors are needed, and more fuel is needed in a time of rising fuel prices.

More subtly it has been discovered that storm surges coming from the west towards the Alaska coastline pick up considerably more energy as they move across open water (which acts as a thermal storage for sunlight) than it does from pack ice (which by reflecting sunlight has lower thermal storage).

Storm Surges

A recent General Accounting Office report found that 90% of Alaska's 213 predominantly Native villages, which are historically situated along rivers and coasts, are affected regularly by floods or erosion *(U.S. Senate 2004)*. Global warming and concomitant changes in the climate have exacerbated these problems. Melting permafrost (see **Thawing Permafrost** below) is more prone to erosion, and in addition, barrier sea ice is coming later in the year leaving coastal villages such as Shishmaref and Kivalina vulnerable to the increasingly violent fall storms. Coastal villages are also increasingly susceptible to flooding as sea levels rise due to thermal expansion and other factors. Combating eroding community infrastructures takes time and labor away from subsistence activities. In addition, the personal and household costs of eroded food caches and housing reduces already decreasing (in constant dollars) household incomes that must be used to purchase subsistence technology (equipment and supplies needed to access and harvest wildlife, fisheries, and plant materials), technology that is wearing out faster as subsistence hunters have to travel further to obtain game. Rural subsistence communities located along rivers also face increased risk from flooding as precipitation regimes fluctuate throughout interior Alaska.

Two communities illustrate the costs of resolving these problems and the profound threats to subsistence activities. Shishmaref's relocation costs have been estimated to be up to 1 million dollars per household. Here are the cost breakdowns for the four alternatives currently being considered:

Alternative One: move the entire community, of approximately 142 households, east to the mainland for a total cost of about $179 million. The costs include: $20 million to move 150 homes, $26 million to move or build a school, clinic, and city hall, $25 million for a new airport, $23 million for roads, and $25 million for water treatment and sewage.

Melting permafrost is more prone to erosion, and in addition, barrier sea ice is coming later in the year leaving coastal villages such as Shishmaref and Kivalina vulnerable to the increasingly violent fall storms.

Alternative Two: relocate all 142 households to Nome—approximate cost of $93 million.

Alternative Three: relocate everyone to Kotzebue—approximate cost of $93 million.

Alternative Four: the community stays in place on Sarichef barrier "island" but fights the erosion with shield rock and other means—total cost $109 million.

Much further south in the Yukon/Kuskokwim area is the community of Newtok with about 65 households. This community has experienced 4,000 ft (1,200 m) of erosion and loses about 90 ft (27 m) of shoreline per year. Estimates indicate that land under the community will erode in the next five years. Relocation costs, including emigration to a nearby site or transplanting all the households to Bethel or Hooper Bay, are estimated between $50-100 million. Some of the relocation alternatives for both communities contain: loss of access to traditional use areas for subsistence activities, loss of history and sense of intact community, and potential loss of social networks and extended kin support integral to sustaining traditional culture.

Thawing Permafrost

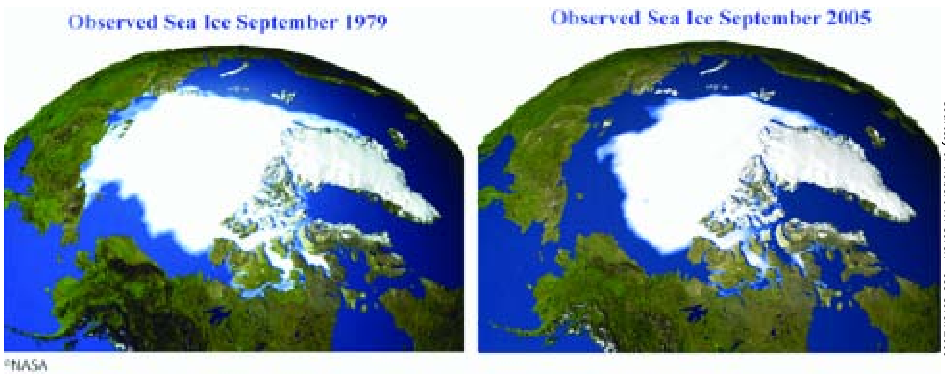
Borehole temperature logs indicate that near-surface permafrost of the Alaska Arctic Coastal Plain and Foothills has warmed approximately 5°F (3°C) since the late 1980s *(McGuire 2003)*. We have already discussed the impacts of storm surges on Shishmaref, however, the thawing permafrost exacerbates the affects of these storms by making the shoreline more vulnerable to erosion. In addition, the discontinuous permafrost is warming at about 0.36°F (0.2°C) per year which is causing wide spread thawing and extensive areas of subsidence. This subsidence is severely affecting buildings and infrastructure such as roads.

How do climate change impacts to urban Alaska infrastructure affect subsistence in rural Alaska? Revenue flows to rural Alaska have experienced sharp declines during the last decade. The urban-dominated Alaska legislature, facing decreasing revenues from oil remittances, has cut programs and monies to rural communities, e.g., school maintenance. Almost all of the employment in rural community comes from federal or state programs, such as part-time employment on capital improvement projects. In some communities, perhaps half the household income is used to purchase subsistence technology. A shrinking revenue flow is already becoming more constricted as the state legislature apportions more and more dollars to sustain urban infrastructure. For example, some roads in the Fairbanks area have to be continually rebuilt due to the impact of thawing of permafrost. Thus, rural communities face a triple whammy from thawing permafrost: 1) coastal communities experience accelerated erosion, 2) there is less or no money to mitigate infrastructural decay, and 3) sharp decreases in employment and wage opportunity decrease available income for subsistence technology in an era where hunters must spend more money on such technology to access and harvest wildlife resources (see **Fisheries** below).

A recent four year study by Brian Riordan of the Bonanza Creek Long-Term Ecological Research Program at the University of Alaska, Fairbanks compared black-and-white aerial photographs from the 1950s, color infrared aerial photographs from 1978 to 1982 and digital satellite images from 1999 to 2002. Riordan concluded that 50% of the ponds in subarctic boreal regions have disappeared in the last 50 years. Much of the remaining ponds have shrunk. These ponds are usually formed when depressions in the ground are filled with rain water but are unable to

Photograph courtesy of North Slope Borough, Department of Wildlife Management

Figure 4. Bowhead whale being processed by residents of the North Slope Borough.



Courtesy of Robert W. Corell—see Corell 2006

Figure 5. Arctic sea ice is at its minimal extent in September. These two photos, reconstructed from NASA data, show the sharp contrast in sea ice retreat by 2005, the lowest concentration on record.

drain due to the fact they are underlain with impenetrable permafrost. Melting of the permafrost lets these ponds drain.

There are at least two important consequences of these disappearing ponds. First, the ponds provide prime habitat for migratory waterfowl, a much anticipated spring subsistence resource. Second and more ominous, the drying landscape may release more carbon dioxide into the atmosphere, further contributing to atmospheric warming, as the carbon stored in the normally wet soil decomposes.

Fisheries

Climate change impacts on fish stocks is extremely complicated. Changes in the velocity and direction of ocean currents affects the availability of nutrients, and in addition, for salmon, freshwater stream temperature and flow can be key indicators for survival and recruitment. To this point, warmer sea surface temperatures and lower ice coverage (since the regime shift in 1975) have had positive outcomes for pollack and flounder, while salmon, with a narrow range of tolerance for temperature shifts, have had record runs in some areas (e.g., Kodiak) while other stocks in western Alaska, the Pacific Northwest and Canada have experienced substantial decreases *(Weller et al. 1999, Criddle and Callaway 1998)*.

Thus, while the Yukon and Kuskokwim Rivers sustained drastically low runs during the last decade, and the state designated many communities from these areas as economic disasters, Copper River runs of sockeye in Southeast Alaska were extremely strong at 1.7 million fish. The strong run in this area maybe linked to the fact that these stocks are independent from Bristol Bay and Bering Sea stocks. Also very disturbing is recent research that ties climate change to increased parasitism in Yukon River salmon. One research project estimates that more than a quarter of Yukon River salmon are being parasitized by *Ichthyophonus,* a disease organism that prior to 15 years ago "had never been recorded in salmon anywhere except by artificial transmission" *(Kokan and Hershberger 2003)*.

Commercial fishing is intrinsically linked to subsistence fishing in that subsistence fish are often taken during commercial fishing activities, and the profits from commercial fishing often help to pay for the technology (boats, outboard motors, guns, snow machines, all-terrain vehicles) necessary to perform subsistence activities.

For example in Unalakleet in 1982, where wildlife resources comprise about 75% of the local diet, the primary source of income for about 115 Alaska Natives was commercial fishing. During this period the average household income was $20,100 per year while the average household cost for subsistence equipment and gas might run $10,000, or nearly half the total household income. One study, *Wolfe (1984:176)* indicated that households in the lower Yukon region might average a harvest of 10,000 pounds of salmon, 90% of which might be sold with the remaining 10% retained for subsistence use.

In the last decade changes in the commercial fisheries have had substantial economic stress on Bering Sea communities. However, as Jorgensen *(1990:127)* notes: When, in 1982, late breakup and very high water destroyed the salmon fishing for Yukon River villages, Unalakleet families connected to families along the Yukon River through marriage packed and shipped huge quantities of fish, caribou, and moose to their affines. (For a more detailed discussion, see *Callaway et al. 1999)*.

However, climate change, even independent of its impacts on fisheries stocks, can have important implications for subsistence fishing. Alex Whiting, a member of the Qikiktagrugmiut in Northwest Alaska, discusses the cultural impacts of late freeze-up on his community. He notes that the youth and elderly depend on strong ice in fall to ice fish for saffron cod and smelt. Late freeze up and a concomitant shorter ice fishing season constrains the interactions of elders and youth during one of their few independent subsistence pursuits and lessens the opportunity for elders to pass on traditional knowledge and ethical values *(Whiting 2002, Huntington and Fox 2005)*.

Winners and losers

Changing climate always brings new winners (pollack, flounder) and new losers (herring, crab, some seal and whale species). Alex Whiting also details the mixed outcomes from these changes for the Qikiktagrugmiut, who reside in the area we now know as Kotzebue—on the plus side

Courtesy of Tony Weyiouanna, Kawerak Transportation Program—see RISA 2004

Figure 6. Two photos of a coastal road in the community of Shishmaref. The first photo was taken around 12:30 pm on October 8, 2002 while the second photo was taken some two hours later. During that period the shoreline had eroded through the road (notice the tire tracks).

he enumerates: better whitefish harvest, better clamming (due to storm surges), better spotted seal hunting, better access to caribou by boat (less by snow machine), better arctic fox harvests, and better access to driftwood. He considers the negative impacts to be: shorter ice fishing season, poor access to Kotzebue for people living outside, rough ice conditions, more danger from thin ice, more erosion and flood problems, and loss of traditional ecological knowledge specific to seal hunting in leads.

Social and Cultural Impacts of Climate Change

The repercussions from climate changes on indigenous arctic communities can be enormous. To this point indigenous institutions seem to be dealing with the changes and deprivations that climate changes seem to be bringing to subsistence activities. Extended social networks based on kinship seem to be buffering the impacts of these changes through wide spread sharing of resources, technology, labor, cash and information *(see Callaway 2003)*. However, more drastic impacts from storm surges or flooding may require whole communities to relocate. Previous research indicates some of the trauma of such actions—decision making within the community is often turned upside down as elders and political leaders find themselves in a completely different context. Hunters esteemed for their abilities and willingness to share are removed from the landscape to which their knowledge is linked. These processes can lead to a pervasive sense of helplessness and lack of control, which can have many social and psychological consequences such as increased levels of drinking and violence.

More ominous concerns, not discussed in this article, are the potential for more systemic impacts to entire ecosystems. Marine productivity, biodiversity and biogeochemistry may change considerably as oceanic pH is reduced through oceanic uptake of anthropogenic CO_2. Increased acidity may impact and eliminate the productivity of phytoplankton, the very basis of the oceanic food web. At the far end of the impact spectrum are suggestions that ancient mass extinctions are correlated with an oxygen depleted ocean spewing poisonous gas as a result of global warming *(Ward 2006)*. Certainly communities dependent on subsistence activities are currently bearing the brunt of climate change and are struggling to adapt to rapidly changing and fluctuating conditions. However, in the not too distant future we all may be taxed beyond our abilities to cope.

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The Frozen Past of Wrangell-St. Elias National Park and Preserve

By E. James Dixon, Craig M. Lee, William F. Manley, Ruth Ann Warden, and William D. Harrison

Photograph by of Robert Ivan

Figure 1. James Dixon and Craig Lee with an NPS helicopter conducting archeological survey on a glacier near Tanada Peak.

(Left) Researchers document an arrow exposed at the base of a steep ice patch.

Photograph by William Manley

As a result of climate change, rare archeological materials are melting from ancient glaciers around the world. Spectacular organic artifacts include prehistoric bows and arrows, spears, hunting tools, baskets, clothing, and even human remains. These unusual discoveries—preserved and frozen in ice for thousands of years—provide an unprecedented glimpse into the lives of ancient people and have captured public attention around the world. Discoveries in Wrangell St.-Elias National Park and Preserve (WRST) provide new insights into cultural development and highlight the exceptional craftsmanship and genius of early people in Alaska.

Alaska national parks are located in areas where glaciers are prominent, and are important regions for archeological and paleoecological research associated with climate change. Strong evidence of recent warming in the Arctic includes historic records of increasing temperature, melting glaciers, reductions in the extent and thickness of sea ice, thawing permafrost, modified ecosystems, and rising sea level *(ACIA 2005)*. These environmental changes are resulting in the emergence of artifacts from ancient ice. The discovery of ancient artifacts presents clear and compelling evidence that very old ice is melting, and Alaska's climate is changing.

Although some of these discoveries have been made on retreating glaciers *(Figure 1)*, most have come from small features that Canadian scientists have termed "ice patches" *(Hare et al. 2004)*. Ice patches frequently occur along the margins of high elevation plateaus and other large, relatively flat, treeless landforms *(Figure 2)*. Most seem to be formed by drifting snow that accumulates to depths sufficient to persist through the entire summer, forming patterns that recur every year *(Holtmeier 2003)*. Animal tracks and feces are commonly observed on their surfaces *(Figure 3)*.

Ice patches are invisible in the winter when the entire landscape is covered by snow. However, in summer they become conspicuous, oasis-like features that attract caribou, sheep, and other animals that seek relief from heat and insects. In addition, the melting snow and ice on the surface produces a supply of fresh water. Accumulated feces and wind blown organic material enrich plant growth. The animals that use these microenvironments attracted ancient hunters who lost weapons, tools, clothing, and other possessions. These artifacts were buried by new snow that eventually became ice. Some ice patches have accumulated over millennia—layer upon layer of ice, artifacts, animal remains, and other fossils.

The exceptional preservation of organic artifacts found at these sites can make them appear to be recent, particularly to the untrained eye. As a result, their full significance may be overlooked. For this reason, it is important to date every specimen and not assume that specimens are recent, or that groups of objects found on the sur-

Photograph by William Manley

Figure 2. Recording organic materials melting from an ice patch.

face are contemporaneous. Once thawed, organic remains decompose or are subject to destruction by scavenging animals and soon disappear.

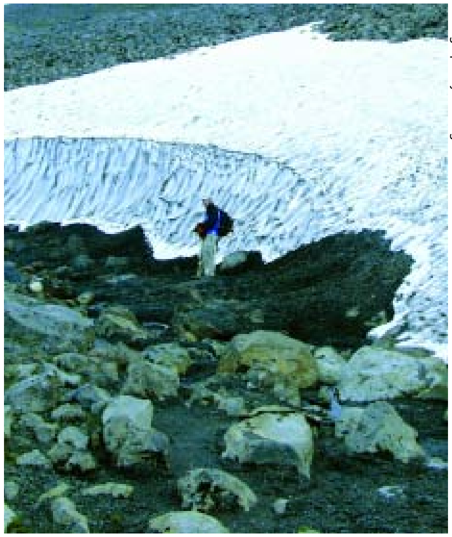
Ice patches are poorly known features of the cryosphere. Research in WRST is continuing with funding from the National Science Foundation, partnerships between scientists in Colorado and Alaska, and participation of the Ahtna Heritage Foundation. By incorporating traditional ecological knowledge of local residents, the function of individual ice patches can be evaluated better. These observations can be correlated with physical data such as elevation, species distributions, local topography, radiocarbon dating, the types of artifacts found, and other information. This synergy between local knowledge and scientific research greatly enhances understanding ice patches and their importance to people.

Ice patch archeology also presents unique challenges. Because it is not feasible or practical to dig test pits in ice, archeologists rely primarily on surface finds. Because artifacts are covered by accumulated snow for much of the year, archeological survey is limited to late summer within the ablation zone, the lower part of the ice patch where melting and evaporation of ice and snow exceeds winter accumulation. Ice patches exhibiting greater ablation than accumulation over the course of a year, or longer, present the best possibility for finding artifacts. Another challenge is the location of the ice patches, most of which are remote and not accessible by road. Field research requires complicated and expensive logistics, including helicopter support.

WRST is the most extensively glaciated area in the United States and its ice-covered portion encompasses 7726 mi^2 (20,100 km^2) *(Post and Meier 1980)*. Research funding and logistic support from the National Science Foundation's Office of Polar Programs facilitated the development of a Geographic Information System (GIS) model to guide archeological survey on ice patches and glaciers in WRST *(Dixon et al. 2005)*. In the summer of 2001 and 2003, aircraft-supported pedestrian surveys were used to assess the archeological potential of the locales identified by the GIS model. The analysis and field survey demonstrated that most glaciers and ice patches do not contain archeological remains, and that there is an urgent need to develop scientific methods to identify specific glaciers and ice patches that are most likely to contain frozen archeological remains.

The artifacts recovered from ice patches are unique and extremely important. Well-preserved organic remains are seldom preserved in archeological sites, particularly sites in Interior Alaska. Commonly, archeologists have only nonperishable remains, such as ceramics and stone, from which to interpret the past. Without the organic artifacts recovered from ice patches, there would be little evidence of the rich material culture essential for survival in these high latitude environments.

The 2001 and 2003 surveys resulted in the identification of five prehistoric sites that contained artifacts ranging in age from 370 to 2880 radiocarbon years before present (B.P.). Three of the five prehistoric sites were associated with ice patches and two with cirque glaciers. All offered good hunting opportunities for caribou and sheep. The artifacts include several unilaterally barbed antler projectile points similar to specimens recovered from the Dixthada site in Interior Alaska *(Rainey 1939)* and from ice patches in the Yukon Territory *(Hare et al. 2004)*. These arrowheads have conical bases for hafting in closed socket arrow shafts. Ownership marks (the "signature" of the individual who made or owned the arrow) are preserved on at least one arrowhead. One arrow was armed with a metal point manufactured from a native copper nugget *(Figure 4)* similar to other arrowheads reported from Interior Alaska and the Copper River region *(Dixon 1985, Rainey 1939, Shinkwin 1979)*. The ends of at least two others exhibit green staining suggesting that they were also tipped with



Photographs by of Craig Lee

Figure 3. Brian Clarke investigates a concentration of caribou dung at the base of a small ice patch.

These arrowheads have conical bases for hafting in closed socket arrow shafts. Ownership marks (the "signature" of the individual who made or owned the arrow) are preserved on at least one arrowhead. One arrow was armed with a metal point manufactured from a native copper nugget similar to other arrowheads reported from Interior Alaska and the Copper River region.

Photograph by William Manley

Figure 4. Projectile points made from copper nuggets were used to arm antler projectile points.

Photograph by William Manley

Figure 5. A recently exposed arrow shaft at the base of a melting ice patch.

Photograph by William Manley

Figure 6. Close-up of sinew lashing used to secure an antler projectile point to an arrow shaft.

copper end blades.

Wooden arrow shafts *(Figures 5-7)* have been radiocarbon dated to between 370 and 850 B.P. (before present). All of the wooden arrow shafts were exquisitely shaped from split wooden staves. Several exhibit traces of red and black pigment. Several preserve spiral impressions resulting from sinew lashing used to secure feathers (fletching) and points to the arrow shafts. At least one arrow was fletched with the feathers of a golden eagle. These types of arrows were used by Ahtna and Upper Tanana Athapaskan people hundreds of years later at the time of Euro-American contact in the 1800s, suggesting that they were left by their ancestors.

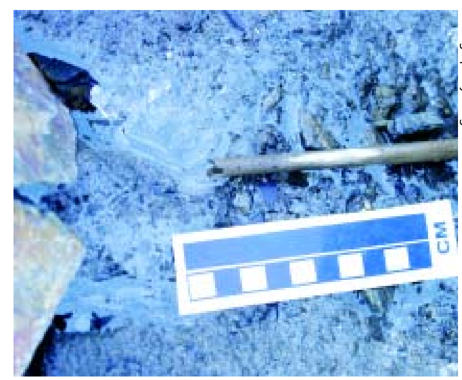
Atlatl darts (lightweight spears propelled with the use of a spear thrower called an "atlatl") are represented by what appear to be shaft fragments recovered from a cirque glacier. A possible atlatl dart (or spear) foreshaft was found at an ice patch. It contains traces of what appear to be red ochre preserved on the stone projectile point, which is secured in a slotted haft by sinew lashing. In addition, almost one-half of a shallow birch bark basket was recovered from the edge of another melting ice patch *(Figures 8-9)*. This circa 650-year-old artifact suggests that ice patches were used for purposes other than hunting.

A total of nine historic sites were discovered during the survey. Six of the historic sites, all probably dating to the Chisana gold rush, circa 1913 AD *(Bleakley 1996)*, were discovered lying directly on glacial ice. Artifacts at these sites include horse hoof trimmings and horseshoe nails (evidence of a horse being shod on the glacier), metal can fragments and other metal objects including a frying pan and a bucket, and a variety of cut wood. The remains of an entire "roadhouse" that provisioned and sheltered travelers traversing a glacier during the 1913 gold rush *(Bleakley 1996)* were observed distributed throughout a 0.4 mi^2 (1 km^2) area on the glacier's surface.

Although difficult to quantify, a variety of methods have been employed to estimate the melting rate of mountain and subpolar glaciers *(e.g., Dyurgerov 2001, 2002)*. These data demonstrate increased glacial melting began in the mid-1960s, and dramatically increase beginning about 1988. The late 1980s increase in glacial melting roughly corresponds to the beginning of reports of archeological discoveries from high altitude glaciers and ice patches around the world. If this trend continues, it is reasonable to assume that archeological and paleontological remains will continue to be exposed over the next few decades. Ice patch research also provides opportunities to better understand ice patch dynamics in relation to climate change and their role in regional ecology. It is possible that these ephemeral sites could largely disappear in the near future. Consequently, it is important to better understand them and collect, study, and preserve the artifacts they contain before they are lost forever.

Acknowledgments

The National Science Foundation, Office of Polar Programs, Arctic Social Sciences Program funded this research (OPP-0097753, OPP-0222490, and OPP-0613002). Field work was conducted under permits issued by the Alaska Regional Office of the National Park Service and Wrangell St.-Elias National Park and Preserve, and with the cooperation of Tad Kehl and Dorothy Shinn, Ahtna Heritage Foundation. Anna Kertulla (NSF–OPP), Ted Birkedal (NPS), and Robert Winfree (NPS) provided valuable advice that facilitated the funding, permitting, and execution of this research. VECO Polar Resources and the NSF Arctic Research Support and Logistics Program provided logistic support. Robert Ivan and Brian Clarke participated in the field survey. Mim Dixon helped edit the manuscript, and Eric Parrish provided technical graphic support as well as analysis of remote sensing. Wrangell-St. Elias National Park and Preserve personnel (Michele Jesperson, Geoffrey Bleakley, and Anne Worthington) helped facilitate the research and field survey. Ole Bates generously shared his knowledge and facilitated radiocarbon dating of one of the projectile points.



Photograph by Craig Lee

Figure 7. The nock end of an arrow shaft melting from glacial ice.

Photographs by William Manley

(Right) Figure 8. Ruth Ann Warden and James Dixon examine a birch bark basket at the base of a retreating ice patch.

(Far Right) Figure 9. The birch bark basket, with a detail of the stitching holes.

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A Disappearing Lake Reveals the Little Ice Age History of Climate and Glacier Response in the Icefields of Wrangell-St. Elias National Park and Preserve

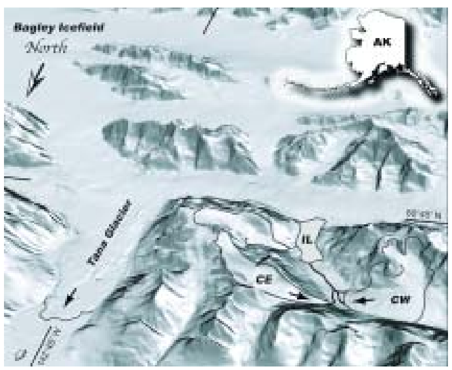

Figure 1. Location and context of Iceberg Lake (IL). Two small glaciers, Chisma East (CE) and Chisma West (CW), provide most meltwater and sediment to Iceberg Lake. Small arrows indicate glacier termini and general flow directions. Scale varies; Chisma Glaciers terminate <3.5 km from the 4-km-long lake. Note figure orientation as shown by north arrow.

(Left) Field assistant Mike Booth works on an outcrop of lake sediments, with stranded icebergs above and a stream traversing the drained lakebed in the background.

Photograph by Michael Loso

By Michael G. Loso, Robert S. Anderson, Daniel F. Doak, and Suzanne P. Anderson

A Disappearing Lake

In the late summer of 1999, artist Hamish Fulton took a long walk through the icefields of Wrangell-St. Elias National Park and Preserve. He had spent months planning the trip, and one highlight of his journey would be a traverse of the remote valley where glacier-dammed Iceberg Lake sits alongside a broad tributary of the Bagley Icefield *(Figure 1)*. The lake is scenic enough, in a land of scenic excess, to grace the cover of a recent hiking guide for the park *(Kost 2000)*, and Fulton was determined to see the lake in person. On the bright sunny morning of August 27, Fulton already had a week of rough hiking behind him as he crested a low pass and paused for his first look at the lake. In the foreground of his view, a creek emerged from the melting terminus of a small alpine glacier. Instead of flowing into a tranquil, iceberg-dotted lake, however, Fulton was surprised to see the creek running wildly across a naked, muddy lakebed, disappearing in the far distance amidst a pile of heavy, dripping icebergs. The lake was gone.

To be fair, the sudden drainage of a glacier-dammed lake is not all that unusual. There are hundreds of such lakes scattered throughout Alaska *(Post and Mayo 1971)*, and many drain on a semi-regular basis. As a lake fills with meltwater from the surrounding mountains, a leak can develop at the base of the ice dam. Impounded water melts and widens the icy hole, turning a trickle into a torrent, and the contents of the lake escape through a subglacial drainage network to emerge from the glacier terminus as a jökulhlaup, or glacier outburst flood. Hidden Creek Lake, one well-studied example of such behavior, has drained—under the Kennicott Glacier and past the town of McCarthy—every summer for at least the last century *(Rickman and Rosenkrans 1997)*.

Still, the drainage of Iceberg Lake was a surprise. Old shorelines, visible on the mountainside above Iceberg Lake, attest to the lake's historic tendency to vary in size *(Figure 2)*. But over the years, local pilots, climbers, scientists, and NPS staff had never seen it drain; there was no record, before 1999, of any catastrophic drainage events. Fulton had witnessed something unprecedented in the history of the park. Intrigued by his photographs of a smooth, fine-grained lakebed *(Fulton 1999)*, we visited Iceberg Lake the following summer to examine its sedimentary record. The lake had only partially refilled, and we found the exposed lakebed dissected by hundreds of small gullies, each draining towards the new 20-60 ft (6-18 m) deep canyon of Chisma Creek, Iceberg Lake's primary inlet stream.

Using Mud to Study Climate

The incipient drainage network was exposing steep-walled, cohesive outcrops of laminated lacustrine sediment. These laminations, known to geologists as varves, represent the annual cycle of sediment deposition into glacial lakes. Coarse sands and silts, brought to the lake by the high flows of summer rivers, contrast with thinner, finer-grained clay deposits that slowly settle out during the tranquil winter. Like tree rings, these alternating bands *(Figure 3)* keep time and record the climate. Each summer/winter couplet represents one year of deposition, and thicker varves typically correlate with warmer summer temperatures.

Only a stable lake can deposit and preserve such delicate sedimentary features, so the repeated jökulhlaups that characterize most glacier-dammed lakes preclude development of a coherent record. Our preliminary examination revealed over 1,000 laminations, confirming Iceberg Lake's unique stability. The features promised a high-resolution record of summer temperatures over a complete climatic cycle, including both the Little Ice Age (A.D. 1600-1850) and the Medieval Warm Period (A.D. 1000-1250) that preceded it. But, before the summer of 2000 was over, Iceberg Lake drained again *(Table 1)*, reminding us that the rapidly eroding gullies that exposed these varves also threatened to destroy them. We found ourselves in a race to decipher the climatic record before erosion removed the rest of the story.

The Little Ice Age (LIA) makes a compelling target for climate reconstructions because it provides the clearest picture of how glaciers have responded, in the past, to climate changes similar to those of the present. Geological evidence of glacier advances during the height of the LIA (around A.D. 1850) is widespread in southern Alaska, including prominent moraine loops around most land-terminating glaciers, and buried forests exposed by contemporary ice-front retreat *(Figure 4)*. Temperatures responsible for these glacier advances have been confidently reconstructed on the basis of tree-ring records *(Wiles et al. 1998)*. A globally recognized period of warm temperatures that preceded the LIA, the Medieval Warm Period (MWP), is less clearly represented in the geologic record. Most evidence of MWP glacier retreat was destroyed by subsequent LIA advances, and the tree-ring record from this region is too short to reconstruct MWP temperatures. As a consequence, we still have little basis for comparing the intensity of contemporary (or predicted) warming and glacial retreat in southern Alaska with that of our most recent pre-industrial warm period.

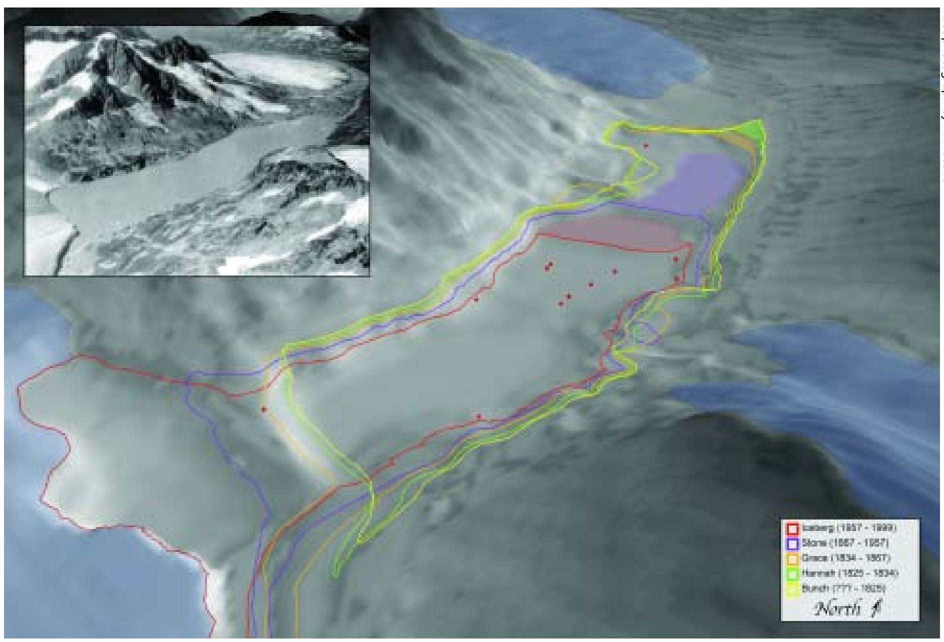

Figure 2. Historic shorelines, lakebed topography, and sample locations at Iceberg Lake. Shorelines (colored lines) and accompanying deltas (shaded) are color-coded, with informal names and intervals of occupation (in calendar year A.D.) in legend. Red dots indicate sites where detailed varve chronologies were collected. Scale varies; long axis of smallest, most recent shoreline is ~4 km. Inset: Aerial photograph of Iceberg Lake, showing Stone shoreline, named in honor of the photographer *(Stone 1963).*

Inset photograph by Kirk Stone

Table 1. Chronology of recent jökulhlaups from post-stable Iceberg Lake, Alaska

Jokulhlaup #	Year	Date†
1	1999	August 27, 1999
2	2000	August 15, 2000
3	2002	August 15, 2002
4	2003	August 3, 2003
5	2004	August 26, 2004
6	2005	August ??, 2005
7	2006	September 6, 2006

† Date of jökulhlaup commencement, ±1 day.

Fieldwork

The record at Iceberg Lake has changed that. In fieldwork conducted between 2001 and 2003, we documented the climate record archived by sediments in the exposed lakebed, and we reconstructed the history of glacial fluctuations around the lake. Taking advantage of the broad outcrops exposed by lakebed incision, we eschewed traditional coring techniques: most description and measurement of the varve record was painstakingly done in situ on cleaned, tagged outcrops. From these outcrops we collected samples for laboratory analyses that included measurements of radiogenic carbon-14 and cesium-137, bulk density, loss on ignition, and sediment grain size. We performed differential GPS surveys to accurately characterize the topography of the lakebed and the surrounding landscape, and also to document the contemporary thickness and extent of glaciers adjacent to the lake. To document the historic extent of those same glaciers, we dated abandoned terminal moraines with lichenometry, a technique that uses the known rates of colonization, growth, and mortality for slow-growing lichen species to date rock surfaces on which those lichens grow *(Loso 2004, Loso and Doak 2005)*. The results of this work tell a coherent story of climate-mediated landscape change beside Alaska's largest icefield.

Measurement, cross-dating, and counting of varves from seven sites in the former lakebed of Iceberg Lake documented continuous sediment accumulation from A.D. 442 to A.D. 1998. Radiocarbon dating, cesium-137 concentrations (from atmospheric nuclear testing), and additional stratigraphic data confirm this chronology, and show that Iceberg Lake has been stably

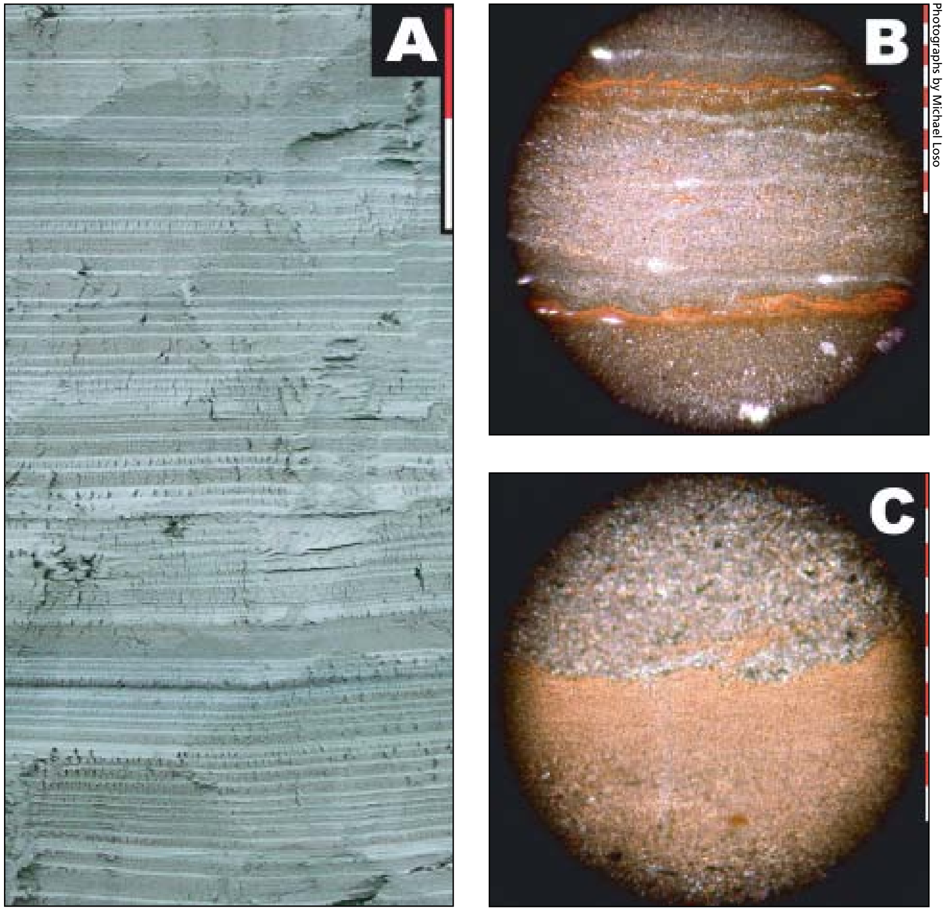

Figure 3. Photographs of varved lacustrine sediments from Iceberg Lake. (A) Varve section photographed *in situ* from a cleaned outcrop. Light gray bands are winter clays. Scale bar is 10 cm. (B and C) Microscope photographs, in plain light, of resin-impregnated, thin-sectioned sediments. Vertical bar in each photo is 1 mm. (B) Typical thin varves showing two reddish winter clays, oxidized subsequent to sample collection. (C) Note winter clay comformably draping underlying summer layer.

impounded by the glacier dam for at least 1,500 years (for details, see *Loso et al. 2006*). Because unstable saturated muds prevented us from examining the oldest (lowest) portion of any of the outcrops, this is a minimum age for the lake, and we are currently planning a more conventional piston coring campaign to document the earliest history of the lake. The resulting chronology of varve thickness measurements *(Figure 5)* nonetheless extends to well before the MWP, and provides an opportunity to compare temperatures from that time period with the subsequent LIA, and of course with the present.

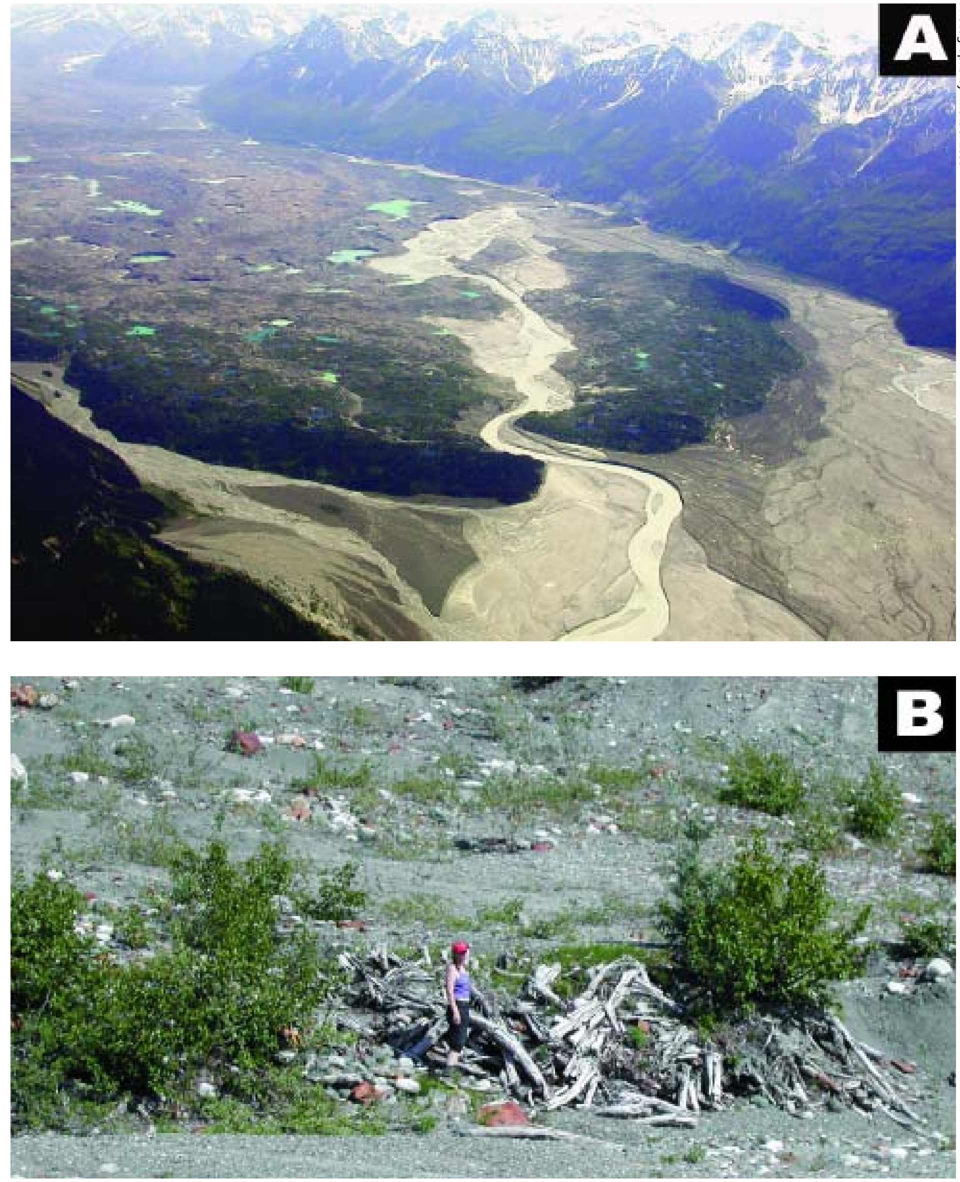

Figure 4. Examples of evidence used for reconstruction of former glacier extents. (A) Terminal moraine loop of the Chitina Glacier, which has retreated several kilometers further up valley at upper left. The Chitina River now cuts through this well-vegetated landform, which remains as evidence of the glacier's maximum advance during the Little Ice Age. (B) Fossil trees in glacial till near the modern terminus of Guyot Glacier, Icy Bay. These trees were overrun by the advancing glacier during a period of climatic cooling, and were subsequently exposed by glacier retreat. Cross-dating of fossil trees like these constrains timing of glacial advances.

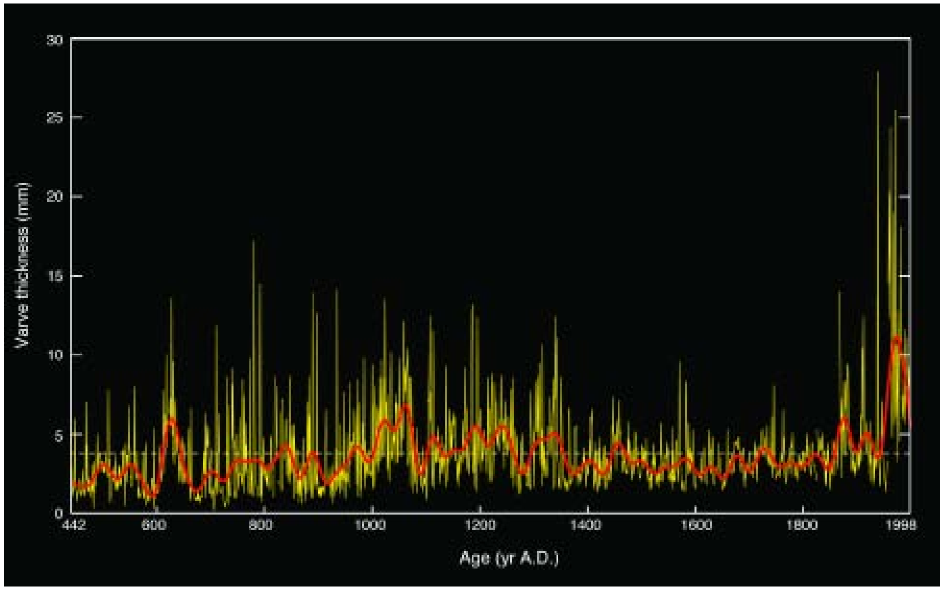

Figure 5. Master chronology of varve thickness measurements compiled from multiple outcrops of lacustrine sediment in Iceberg Lake. Yellow line shows annual measurements. For clarity and to show general trends, red line shows data smoothed with a 40-year low pass filter. Note slightly thicker varves during Medieval Warm Period as compared to those during the Little Ice Age.

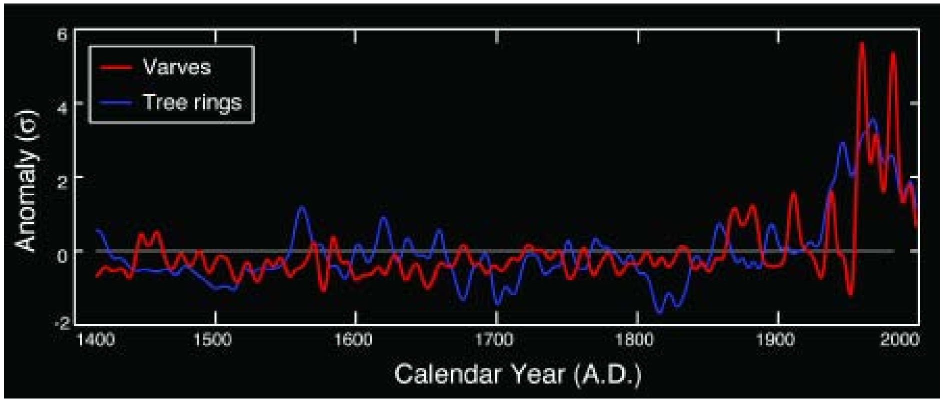

Figure 6. Comparison of the recent portion of the Iceberg Lake varve chronology (red line) with tree ring-width anomalies (blue line) from the adjacent Wrangell Mountains *(Davi et al. 2003),* showing strong correlation between the two records (correlation = 0.62, p<<0.001). Smoothed versions of both records are shown, but correlation was calculated with raw (annual) data.

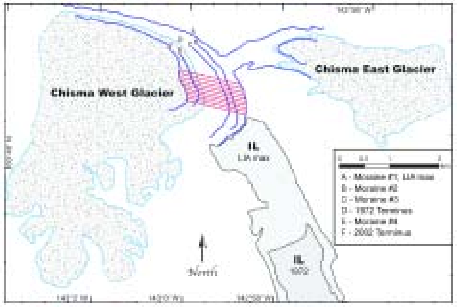

Figure 7. Terminus positions of the Chisma Glaciers. The oldest and most extensive glacier advance, shown by terminus position A (moraine #1), demonstrates that the Chisma West and Chisma East Glaciers were connected at the height of the Little Ice Age, and terminated near a strandline that marks the LIA-maximum highstand of Iceberg Lake (IL). Subsequent glacier retreat history is marked by terminus positions B-F. The mapped outlines of Chisma West and Chisma East glaciers and of the smaller shoreline of Iceberg Lake are derived from 1972 aerial photos. The larger, LIA maximum shoreline is from Loso et al. *(2004).* Glacier terminus positions were measured along ten transects shown by parallel dashed red lines.

Climate and Glacier Response

As mentioned earlier, theory suggests that warm temperatures are correlated with thicker varves, specifically because warm summer temperatures heighten the melt of both seasonal snow cover and alpine glaciers, increasing the discharge and sediment transport capacity of rivers that feed the lake *(Leonard 1985).* To test this theory at Iceberg Lake, we compared our varve thickness record with the longest annual resolution regional climate reconstruction available: an almost 600 year-long record of growing season temperatures based on tree rings from the nearby Wrangell Mountains *(Davi et al. 2003)*. The two records are strongly and significantly correlated with each other between A.D. 1415 and 1998 *(Figure 6)*, suggesting that the entire varve chronology can be interpreted as reflective of summer temperatures.

The data tells us that Iceberg Lake was glacier-dammed, stable, and accumulating the thinnest varves of its known history when the measured varve record begins in the early fifth century A.D. *(Figure 5)*. The lakebed does not record the onset of this cold period, but is consistent with evidence for glacial advances around this same time in the mountains north and south of Iceberg Lake, based on cross-dating of buried trees *(Wiles et al. 2002, Calkin et al. 2001)*. Warming is marked by an increase in varve thickness and inferred temperatures that are sustained between A.D. 1000 and 1250, peaking around A.D. 1050 in a clear manifestation of the MWP. The LIA is recorded in the varve record as a period of thin varves between A.D. 1500 and 1850, followed by a dramatic increase in varve thickness that culminates in unprecedented values during the mid to late-1900s.

These results are consistent with known regional and global climatic trends, including widespread instrumental evidence for rapid twentieth century warming, and they provide the first detailed evidence that contemporary southern Alaska temperatures are significantly higher than temperatures during the MWP. Evidence of glacial activity in the Iceberg Lake basin reinforces this conclusion. Lichenometric dates on terminal moraines downstream of Chisma Glacier, the small alpine glacier that provides meltwater and sediment for Iceberg Lake's primary inlet stream *(Figure 7)*, show that the glacier terminus retreated rapidly in the late twentieth century in response to rapid warming *(Figure 8)*.

We have no record of that glacier's behavior during the MWP, but the lake itself provides another form of evidence for how nearby glaciers responded to MWP warming. We examined dozens of outcrops throughout the muddy bottom of Iceberg Lake, and the varve record was in all cases uninterrupted by signs of large-scale erosional unconformities. This continuity of sedimentary layers in Iceberg Lake precludes the possibility that catastrophic lake drainage events—which would have resulted in widespread lakebed erosion comparable to that seen since 1999—occurred at any time during the last 1,500+ years. Contemporary jökulhlaups reflect climatically induced thinning of the large glacier that impounds Iceberg Lake; the absence of evidence for similar events in the varve record strongly argues that the MWP was not warm enough to prompt similarly extensive glacier thinning and retreat, suggesting that contemporary glacier retreat is unprecedented over the last 1,500 years.

Conclusions

Wrangell-St. Elias National Park and Preserve is the park system's primary showcase for glacial landscapes, and the landscape-scale consequences of a warming climate will be central to the resource management and interpretive missions of the National Park Service for the foreseeable future. Iceberg Lake's record of late Holocene climate and glacier response provides researchers, NPS staff, and the general public with important context for understanding and interpreting one increasingly obvious sign of contemporary warming: glacial retreat. Climate and glacier dynamics vary tremendously across southern Alaska, and further research will be needed to judge the broader applicability of our conclusions in other regions. But on the northern margin of the Bagley Icefield, it appears that twentieth century warming is more intense, and accompanied by more extensive glacier retreat, than the Medieval Warm Period or any other time in the last 1,500 years.

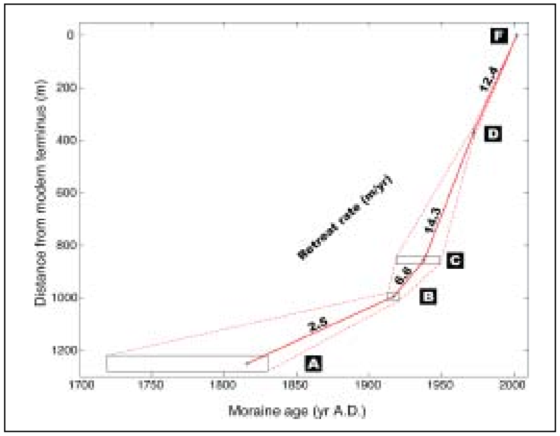

Figure 8. Post-Little Ice Age retreat history for the terminus of the Chisma Glacier, showing acceleration of retreat in the early twentieth century. The ages of moraines A, B, and C (letters correspond to Figure 7) are estimated using a new lichenometric technique; moraines D and F are from aerial photography and GPS surveys. Moraine E was not dated. Distances include 95% confidence intervals based on standard deviation of measurements from 10 transects. The dotted red lines thus enclose overall confidence limits for the retreat history. Mean retreat rate for each interval is shown in bold print.

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Post Little Ice Age Glacial Rebound in Glacier Bay National Park and Surrounding Areas

(Left and Above) Researchers Chris Larsen and Ellie Boyce set up GPS units over benchmarks set into bedrock at various locations in Glacier Bay.

Photographs by R.J. Motyka

By Roman J. Motyka, Christopher F. Larsen, Jeffrey T. Freymueller and Keith A. Echelmeyer

Introduction

The fastest measured rates of uplift in the world today are in Southeast Alaska: in Glacier Bay National Park and east of Yakutat *(Figure 1)*. The first measurements of this rapid uplift were done the mid-twentieth century through tide gauge studies, which suggested that land in the Glacier Bay region was emerging at 1.18 in/yr (30 mm/yr) and faster in Glacier Bay *(Hicks and Shofnos 1965)*. However, the cause of the uplift was still being debated when we initiated our investigations in 1998. To determine whether this uplift was driven by tectonics or glacial rebound we embarked on a field program that included:

1) repeating and reviewing the original tide gauge measurements,
2) measuring the current rates of uplift with modern GPS geodetic techniques,
3) defining the regional pattern of uplift,
4) determining when this episode of uplift began, and
5) assessing the total amount of uplift that has occurred.

Uplift Measurements

We used three complimentary methods to measure uplift:

1) precision GPS geodesy,
2) relative sea-level change from tide gauge measurements, and
3) raised shoreline studies.

Precision GPS geodesy has many distinct advantages—it can be done anywhere there is stable bedrock, thus allowing much broader spatial coverage than the other two methods; researchers can measure benchmark positions relative to a global reference frame with high accuracy (± 0.08 in, ± 2 mm); and it measures both vertical changes and horizontal motion, latter of which is very important in this tectonically active region. We established over 70 measurement stations distributed across the region *(Figure 2)*, with each site typically having two to four occupations over three to six years. By assessing the change in position over these intervals, we determined bedrock motion on an annual basis. The results of our GPS investigations for vertical motion are shown in *Figure 2*. A double bulls-eye of contours delineates two centers of rapid uplift in Southeast Alaska: over Glacier Bay (1.18 in/yr, 30 mm/yr) and over the Yakutat Icefield (1.26 in/yr, 32 mm/yr) *(Larsen et al. 2005)*. Uplift rates decrease smoothly away from these peaks. The uplift pattern documented here spans an area of over 40,000 mi^2 (100,000 km^2). As we shall see later, the centers of peak uplift coincide with places that have experienced some of the greatest losses of ice.

The tide gauge data used in our second method come from permanent National Ocean Service (NOS) gauges, NOS temporary gauges and our own temporary gauges *(Larsen et al. 2003, 2004)* for a total of 22 sites *(Figure 3)*. Temporary tide gauges typically record sea-level over the course of one or more monthly tidal cycles, and the

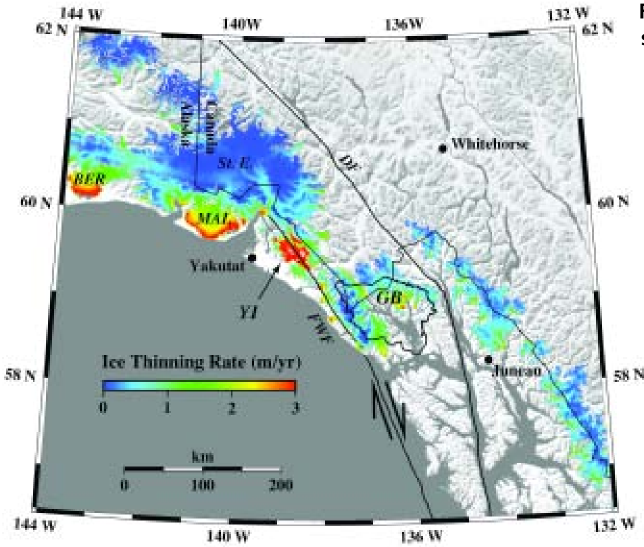

Figure 1. Location map, showing tectonic setting and present day glacier wastage *(from Larsen et al. 2005).* Ice thinning rates follows Arendt et al. (2002). The fastest changes are occurring at lower elevations, such as the termini of the Bering (BER) and Malaspina (MAL) glaciers. The Yakutat Icefield (YI) is an exception, where thinning rates are about three times greater than the regional average and are driving the greatest ongoing unloading in Southeast Alaska. The Glacier Bay Little Ice Age Icefield is outlined (GB). Most of this icefield disappeared over the last ~250 years. Tectonic deformation along the North America Pacific Plate boundary occurs as strike-slip motion on the Fairweather Fault (FWF), and to a lesser degree, the Denali Fault (DF).

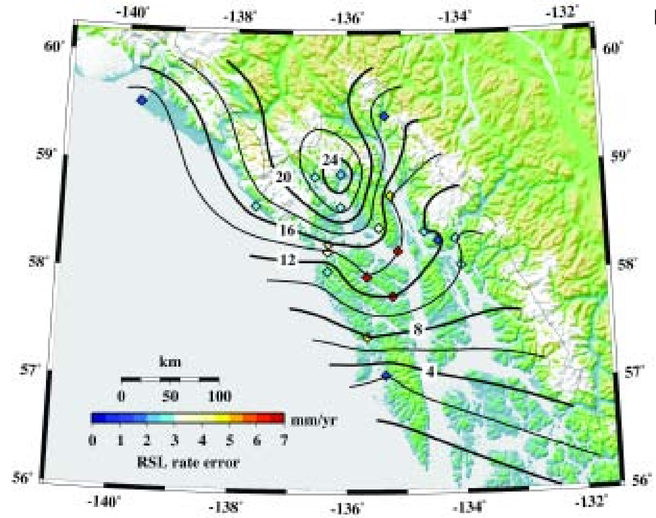

Figure 3. Negative sea level rates from tide gauge data (from *Larsen et al. 2004*). Contour interval is 0.08 in/yr (2 mm/yr). Red diamonds indicate tide gauge sites.

elevation of the gauge is then surveyed relative to a local network of benchmarks. When this procedure is repeated several decades later, sea level change can then be found relative to the benchmarks. The average overall uncertainty in this method is $1\sigma = \pm 0.2$ in/yr (5 mm/yr). The pattern of sea level changes found at the tide gauge sites indicates that the fastest sea level changes in Southeast Alaska are found in Glacier Bay *(Figure 3)*. This finding is in general agreement with Hicks and Shofnos *(1965)*, although we determined that the peak uplift rate found by Hicks and Shofnos at Bartlett Cove is almost certainly biased by unstable reference benchmarks there. After we rejected the data from this point, we found that overall the pattern and magnitude of regional sea level rates have remained essentially constant at the level of measurement accuracy since the time of the earliest rate measurements *(Larsen et al. 2005)*. The pattern of sea level rates also agrees well with the pattern of uplift rates from GPS measurements within the Glacier Bay region *(Figure 2)*.

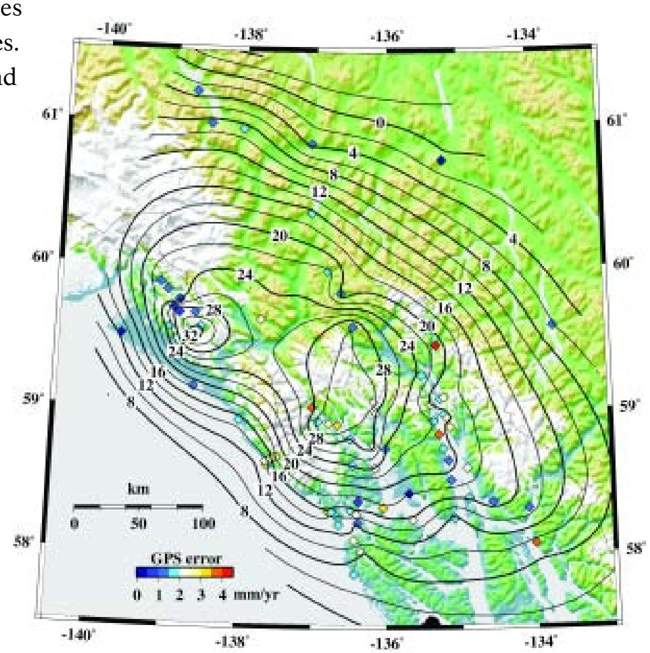

Figure 2. GPS uplift observations in Southeast Alaska *(from Larsen et al. 2005).* GPS uplift rates are in mm/yr; contour interval is 0.08 in/yr (2 mm/yr). GPS stations are shown with diamonds, colored according to the uplift rate error at each site as indicated by the color scale bar. Peak uplift rates are found in Glacier Bay (southern peak) and the Yakutat Icefield (northern peak).

In the third method, we measured raised shorelines at 27 different coastal sites. Coastal regions in and around Glacier Bay National Park clearly show the effects of rapid uplift through recent land emergence, young shoreline forests, new shoals, raised shorelines, and wave-cut benches *(Motyka 2003)*. Raised shorelines were identified by:

1) a wave cut step or riser in the slope,
2) a change in thickness of organic-rich soil,
3) termination of beach deposits, and/or
4) an abrupt change in age of trees *(Figure 4)*.

The difference in elevation between the raised shoreline and the current maximum high tide level provided us with the total amount of sea-level change. Dating tree ages just below the raised shoreline provide a minimum estimate of the onset of land emergence *(Motyka 2003, Larsen et al. 2005)*. The average overall uncertainty in estimating change in shoreline elevation is $1\sigma = \pm 1$ ft (0.3 m). The results shown in *Figure 5* show that the total sea level change found at the raised shoreline sites also describes a regional pattern surrounding Glacier Bay. Quite notably, the greatest amount of sea level change occurs at the sites closest to where the peak rates of uplift and sea level fall are found. Dates for the initiation of emergence is estimated to have begun 1770 ± 20 AD, the same period that Glacier Bay and other regional glaciers began retreating from their Little Ice Age maximums *(Motyka and Beget 1996, Larsen et al. 2005)*.

Glacial Rebound

The correlation of the onset of uplift with the retreat of glaciers in and around Glacier Bay makes unloading of the earth's crust through loss of glacier ice a prime suspect for driving the regional uplift. This is because one of the consequences of changes in glacier ice mass is a readjustment of the earth's crust and underlying layers in response to the changing weight, a process known as "glacial isostatic adjustment" (GIA). The effect is akin to the well-known Archimedes Principle, e.g., when you add or remove weight in a floating boat, it will sink or rise in the water. The earth's crust responds in a similar way but with a substantial time lag: unlike water, the material beneath the earth's crust (know as mantle) is extremely viscous and it takes considerable time (centuries to millennia) for it to respond to a change in load. Examples of long lasting viscoelastic response are well documented in regions that were covered by continental ice sheets during the Last Glacial Maximum 16,000 years ago, e.g., Hudson's Bay and Scandinavia. In a similar way the rapid uplift rates observed in Glacier Bay are related to recent ice loss. To test this hypothesis, our next step was to determine how much glacier ice has been lost in the region and whether GIA response to this changing load could account for the entire strong uplift signal. If so, then the results would also tell us much about the properties of the earth's crust and mantle in this region.

Glacier Ice Loss

Just over 250 years ago a vast ice field blanketed much of what is now Glacier Bay National Park. The main exit for much of this ice was into Icy Straits *(Figure 6)*. The period over which this ice accumulated and expanded to fill the entire bay is known as the Little Ice Age (LIA), which began during the thirteenth century in southeastern Alaska. During the mid-eighteenth century a period of climatic warming appears to have affected the entire region as evidenced by a number of glacial retreats starting about this time *(Motyka and Beget 1996)*. Glacier Bay was no exception and this warm period triggered a dramatic calving retreat of glacier ice that lasted into the twentieth century.

Glaciers leave behind tell-tale signs of their maximum expansion, and we utilized these markers to reconstruct what Glacier Bay looked like at its LIA maximum. These signs include forest trimlines, lateral moraines, terminal moraines, and glacier outwash. We used light aircraft overflights to identify these geomorphic markers as

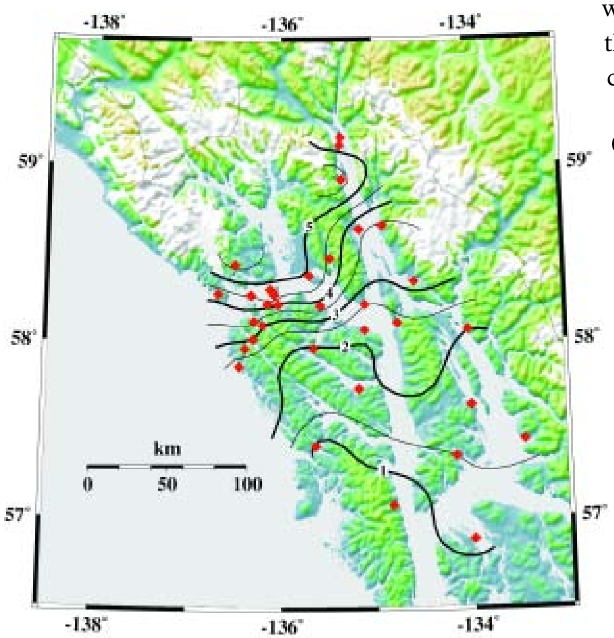

Figure 5. Relative sea level change (from *Larsen et al. 2005*). Raised shoreline sites are shown with red diamonds. Contour interval is 1.64 ft (0.5 m).

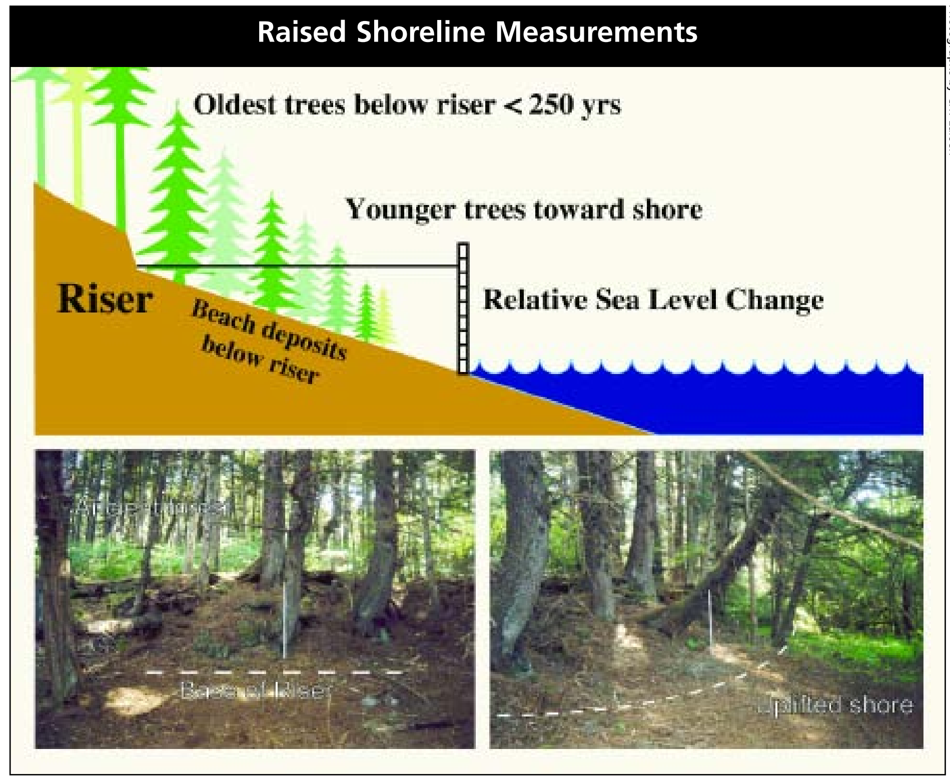

Figure 4. Schematic of a typical raised shoreline measurement in Southeast Alaska (above), and photographs of a site at Swanson Harbor (below). Dendrochronology of Sitka spruce *(Picea sitchensis (Bong.) Carr)* rooted at the base of the raised shorelines brackets an onset date of 1770 AD (± 20 yrs) for the current uplift. Raised shoreline heights, determined from level-line surveys, are greatest at those sites closest to Glacier Bay (19 ft/5.7 m measured maximum) and diminish to less than 3.3 ft (1 m) 93 mi (150 km) southeast of the bay, a pattern similar to present day uplift rates.

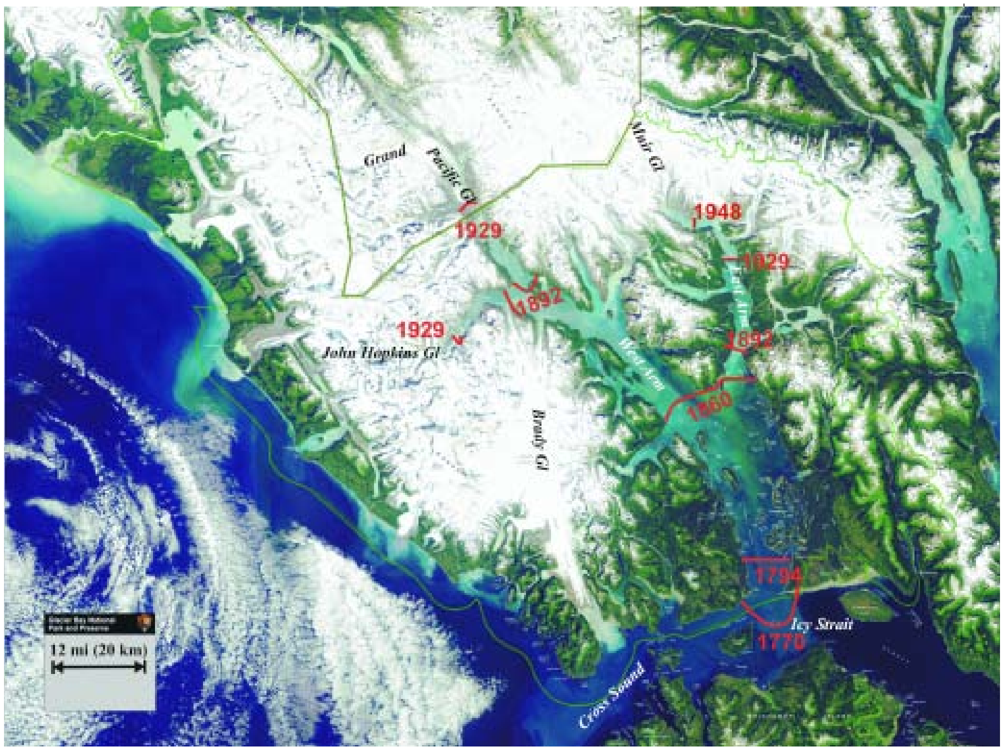

Figure 6. This image was created using satellite imagery, collected on August 1, 1999, and August 10, 2000. The red lines mark glacial extent over the last 200 years. We know from moraines and submarine topography that the terminus extended into Icy Strait, which tree ring dating puts at about 1770 AD. The icefield underwent a rapid calving retreat soon after, retreating 75 mi (120 km) in 160 years in the West Arm. Some tidewater glaciers are now re-advancing, most notably John Hopkins and Grand Pacific glaciers, while others continue to retreat, e.g., Muir Glacier. (Image by NPS Landcover Mapping Program)

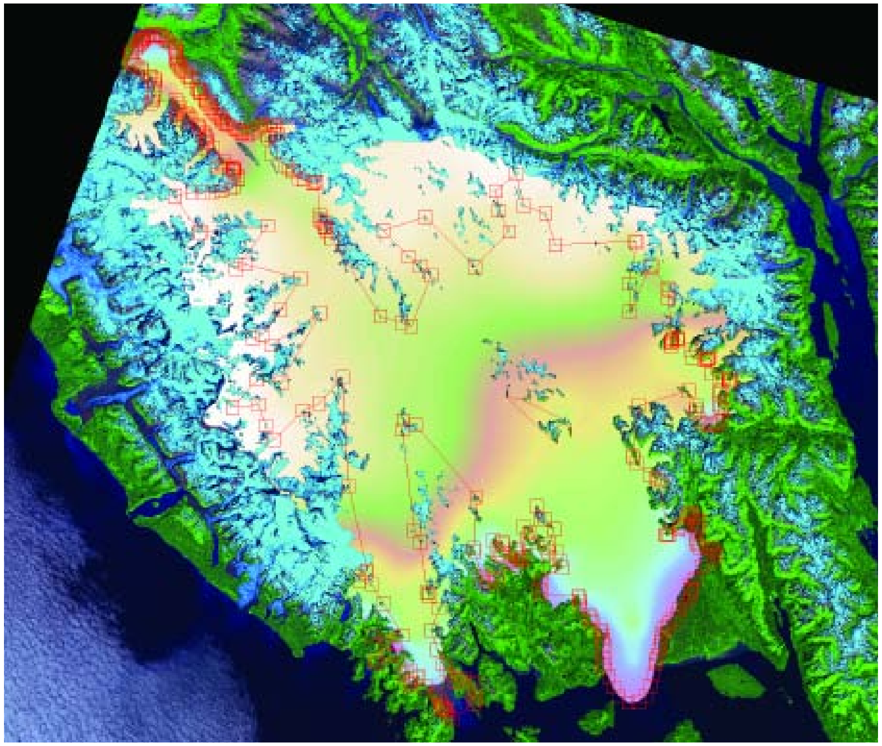

Figure 7. Reconstruction of LIA maximum glacier surface in Glacier Bay (~1750 AD) *(modified from Larsen et al. 2005).* The LIA maximum ice surface was determined by mapping geomorphic markers shown as squares (trimlines, lateral moraines and terminal moraines). These markers were identified through aerial inspection, vertical airphoto analysis, high resolution digital elevation model (DEM) analysis, and field observations. Modern-day glacier analogues were used to construct the Glacier Bay LIA icefield surface from the geomorphic markers. This surface was then differenced with a DEM of present-day topography to determine ice thickness change since LIA.

well as analysis of vertical airphotos, satellite imagery and digital elevation models to determine heights and locations of these indicators of maximum ice extent. Our results in *Figure 7* show that Glacier Bay contained a huge continuous icefield up to 0.9 mi (1.5 km) thick that covered more than 2350 mi^2 (6000 km^2) at the peak of the LIA (1770 AD). Rapid calving and associated upstream drawdown lead to its collapse in less than 160 years, with the main trunk of the icefield retreating 75 mi (120 km) in fjords as deep as 1640 ft (500 m). Using our reconstruction we calculated that an ice volume of about 820 mi^3 (3450 km^3) was lost above sea level during the post-LIA collapse, comparable in volume to Lake Huron, and equivalent to a global rise in sea level of nearly 0.4 in (1 cm). An additional 60 mi^3 (250 km^3) of below sea level glacier ice was lost in the fjords. To our knowledge this retreat in Glacier Bay is the largest post-LIA deglaciation in the world.

Ice continues to melt in Glacier Bay and other ice fields in the region *(Larsen et al. 2006)*, in some cases at an accelerating rate as documented in separate programs *(Arendt et al. 2002)*. This ongoing ice melt continues to contribute to rebound effects already underway.

Glacial Rebound Model

Armed with knowledge of the region's ice load history, our next task was to construct an earth model that would satisfy the uplift observations. If we could produce a statistically valid model that satisfied our data constraints, then we could show that the regional uplift is primarily a consequence of GIA associated with post-LIA deglaciation of southern Alaska. We tested various earth models against the uplift observations *(Larsen et al. 2004, 2005)*, and found that GIA could completely account for the observed uplift. The results also provided robust constraints of lithospheric and asthenospheric structure *(Figure 8)*. Futhermore, the models indicate that GIA from the collapse of Glacier Bay is about at the halfway point and that this glacial rebound driven uplift should continue for several more hundred years. Of course, additional ice loss from regional glaciers continuing their trend of wastage and thinning will only add to this effect.

Conclusions

In Southeast Alaska we have measured the world's fastest present-day isostatic uplift using GPS geodesy combined with studies of raised shorelines and tide gauges. The uplift pattern documented here spans an area of over 40,000 mi² (100,000 km²) centered on the coastal mountains along the Gulf of Alaska *(Figures 2, 3, and 5)*. The data set depicts a regional pattern of uplift, with peaks of 1.18-1.26 in/yr (30-32 mm/yr) centered over upper Glacier Bay and Yakutat Icefield. The peak uplift rates are found in regions that have experienced the highest rates of ice loss. Raised shorelines that date back to 1770 ± 20 AD indicate total sea level fall in the range of 3.3 to 18.7 ft (1.0 to 5.7 m). The onset of uplift measured at the raised shoreline sites correlates with when the Glacier Bay Icefield began its dramatic collapse. GIA modeling results provide robust constraints on lithospheric elastic thickness, asthenosphere thickness and asthenosphere viscosity *(Larsen et al. 2005)*. The simultaneous onset of unloading and sea level change is a direct observation of the causal relationship between glacial unloading and the region's uplift. Climate changes rather than tectonic forces have primarily forced these regional sea-level changes.

These adjustments to LIA glacier loading and unloading are producing significant stresses on the earth's crust in Glacier Bay, which can affect seismicity and regional tectonics. The rising land is also continually changing the shorelines and geomorphic texture of shoreline throughout the park and causing changes in hydrologic patterns, erosion and sedimentation. All these changes have a direct impact on the ecosystems of the park.

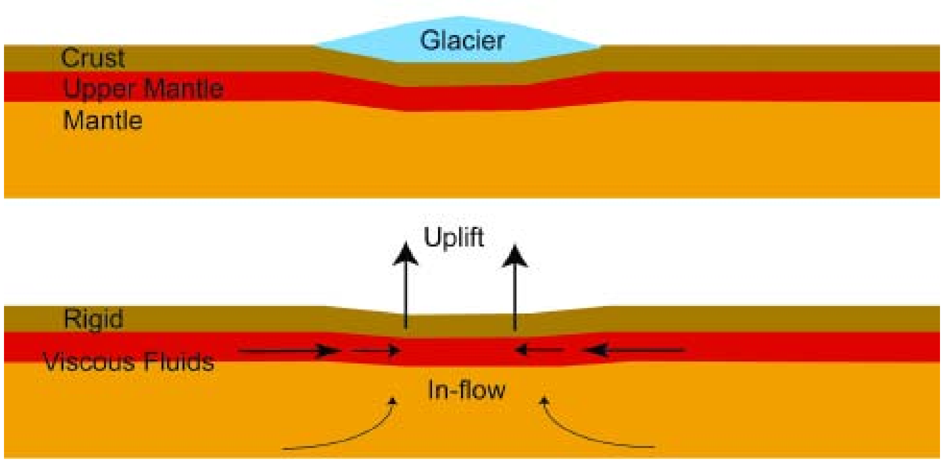

Figure 8. A diagram of the earth models used in our study. In the upper panel, a depression has formed on the surface of the earth, where the weight of the glacier has pressed down the rigid crust, displacing some of the viscous mantle beneath. When the glacier melts, the crust rebounds causing uplift, which is prolonged somewhat by the slow response of the viscous mantle flowing back into equilibrium.

Acknowledgments

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Photograph by Page Spencer

Visualizing Climate Change—Using Repeat Photography to Document the Impacts of Changing Climate on Glaciers and Landscapes

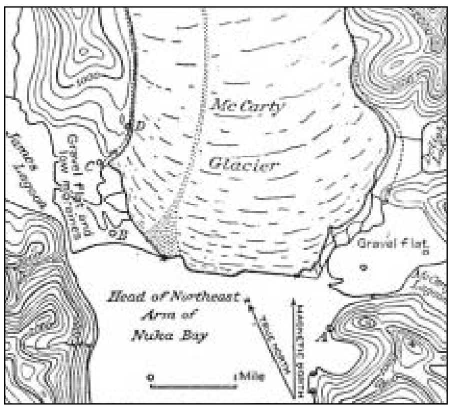


Figure 1. Sketch map of the terminus of McCarty Glacier and upper Nuka Bay made by Grant and Higgins *(1913)* in July 1909. The point labeled 'A' is the location from which the photographs in *Figure 4* were made. Maps like this one are very useful in relocating historical photograph locations. Unfortunately, they are associated with less than 10% of the historical photographs found.

By Bruce F. Molnia, Ronald D. Karpilo, Jr., Jim Pfeiffenberger, Doug Capra

Introduction

Repeat photography is a technique in which a historical photograph and a modern photograph, both having the same field of view, are compared and contrasted to quantitatively and qualitatively determine their similarities and differences. This technique is being used in both Kenai Fjords National Park (KEFJ) and Glacier Bay National Park and Preserve (GLBA) to document and understand changes to the landscapes of both parks as a result of changing climate. The use of repeat photography to document temporal change is not new. What is unique here is the systematic approach being used to obtain photographic documentation of landscape change for every fiord in KEFJ and GLBA. Through analysis and interpretation of these photographs, both quantitative and qualitative information is extracted to document the landscape evolution and glacier dynamics of both parks.

Initially, the emphasis of this study was on documenting the post-Little Ice Age (LIA) behavior of glaciers in both parks. However, the focus has expanded to a much broader documentation of landscape evolution and glacier change in response to post-LIA climate change. Repeat photography is being used to assess changes in sedimentation, sediment distribution, vegetation type and distribution, vegetative succession, wetland location and extent, hydrology, shoreline characteristics, and glacier extent, thickness, and terminus position. Glacier retreat, resulting in the exposure of new land surfaces, is the process that governs all of the other parameters being monitored.

A survey of recent Alaska glacier behavior *(Molnia 2006)*, confirmed that more than 99% of all of the valley glaciers in Alaska are currently retreating. Therefore, it is not surprising that all of the landscapes being observed in KEFJ are characterized by long-term glacier retreat. In GLBA the picture is more complicated. There, although all East Arm glaciers have experienced nearly continuous retreat, several West Arm glaciers have undergone significant periods of advance during parts of the twentieth and early twenty-first centuries. However, all these glaciers have experienced significant, post-LIA ice loss.

In all cases, the driver for landscape and glacier change appears to be an Alaska-wide increase in air temperature, which may also be accompanied by an increase in precipitation. Groisman and Easterling *(1994)* reported that between 1968 and

National Park Service and Dallas Museum of Natural History photograph

1990 precipitation increased an average of 30% over the region west of 141° W. longitude (i.e., all of Alaska except southeastern Alaska). Since 1949, Alaska weather station temperature data are characterized by a significant increase in mean annual air temperature. A compilation of mean annual and seasonal air temperatures for Alaska's 20 first-order observing stations, prepared by the University of Alaska Geophysical Institute's Alaska Climate Research Center, confirms the average temperature change over the last five decades was an increase of ~3.6°F (~2.0°C) *(Alaska Climate Research Center 2005)*. Interestingly, more than 75% of this warming occurred prior to 1977. Most of the warming occurred in winter and spring, with a smaller change in summer. Prior to 1949, air temperature data were far less abundant and less reliable. Stations with longer-term records do not indicate the significant warming trends seen post-1949.

During the LIA (13th to 19th centuries), glacier ice covered most of KEFJ and GLBA. As recently as the mid-eighteenth century, fiords of both parks were filled by massive glaciers that in some instances, extended beyond today's southern park boundaries. In KEFJ, glacier retreat began during the second half of the nineteenth century, while in GLBA retreat began much earlier, perhaps ~1750 AD. For example, McCarty Glacier in KEFJ has retreated ~15 mi (25 km) from its LIA maximum position, while Northwestern Glacier has retreated ~9 mi (15 km). In GLBA, Muir Glacier has retreated more than ~68 mi (110 km), with ~25 mi (40 km) of retreat occurring after 1900.

Methods

The key to successful repeat photography is finding high quality historical photographs that become the baseline for comparison with modern images. For GLBA, more than 1,400 late nineteenth century and early twentieth century, ground- and sea surface-based photographs have been found. More than half of these depict glacier termini and related features. About 300 are from the nineteenth century, with the earliest predating 1885. Sources include the National Archives, the Alaska State Library, the National Snow and Ice Data Center (NSIDC), the GLBA archive, travel narratives, scientific publications, internet sites, antique dealers, and the U.S. Geological Survey Photographic Library located in Denver, Colorado. More than 800 of these photographs have been acquired by the lead author and compiled into a digital database. Analog photographs (paper prints) are scanned and converted to digital images.

Nearly all of the historical photographs lack important elements of metadata, most significantly location, camera specifics, lens information, and film and exposure data. In most cases, only the name of the photographer and the date of acquisition are known. No photographs have latitude and longitude of the collection site. For GLBA, historical photographs used were made by H.F. Reid (1890-1892), Frank LaRoche (~1890), the International Boundary Commission (~1895-1915), G.K. Gilbert (1899), C.W. Wright (1906 and 1931), J.B. Mertie (1916), A.H. Brooks (1924), W.O. Field (beginning in 1926), and Juneau-based commercial photographers Winter and Pond (~1895-1920), among others. Few of these photographs have been published.

During the summers of 2003-2005, ~125 GLBA locations depicted in historical photographs were revisited. Prior to field work, locations were determined by comparing historical photographs with topographic maps and aerial photographs. However, actual locations for most sites were only found through a trial and error field process in which features on the historical photograph were matched by comparing the spatial relationships between mountain peaks and foreground features. This revealed that a surprisingly large number of historical photographs were made from the decks of boats. Several were made from the surface of no longer existing glaciers. At approximately 25% of the land-based locations, cairns were found and reoccupied.

At each site, we recorded a standard set of data and information, including date and time of visit, latitude, longitude, and eleva-

Visualizing Climate Change – Using Repeat Photography to Document the Impacts of Changing Climate on Glaciers and Landscapes

Location of paired images photographed in Kenai Fjords National Park.

2 **Figure 2. A pair of northeast-looking photographs taken from about 5 mi (8 km) north of the mouth of McCarty Fjord, KEFJ. The photographic pair documents significant changes that have occurred during the 95 years between July 30, 1909 (Figure 2A) and August 11, 2004 (Figure 2B). Figure 2A shows the east side of the retreating tidewater terminus of McCarty Glacier. The gravel bar located in the upper center of the photograph is the same one shown on the Grant and Higgins sketch map in Figure 1. Figure 2B shows the terminus of McCarty Glacier has retreated out of the field of view. A small part of the glacier, located more than 10 mi (~16 km) up McCarty Fjord is visible above the left of center.**

3 **Figure 3. A pair of west-looking photographs taken from the same shoreline location of Pedersen Glacier, Aialik Bay, KEFJ. Figure 3A, an early twentieth century postcard shows the terminus of Pedersen Glacier, fronted by an iceberg filled lagoon. Figure 3B, a 2005 photograph, documents the retreat of the glacier and the formation of a vegetated, outwash plain-wetland complex in the area exposed as the glacier retreated. The glacier has retreated about 1.1 mi (1.75 km).**

4 **Figure 4. A pair of north-looking photographs taken from the same location on the backbeach south of Bear Glacier, KEFJ. Figure 4A shows the eastern terminus of Bear Glacier, fronted by a small outwash plain and a small lagoon in July 1909. In Figure 4B, the only part of Bear Glacier visible in August 2005 is a tributary descending from the mountains. Bear Glacier has thinned by more than 660 ft (200 m), and the eastern terminus has retreated more than ~ 2 mi (3 km). The lagoon has been filled with sediment and the outwash plain to the north is covered by grasses, wildflowers, shrubs, and trees.**

5 **Figure 5. A pair of northwest-looking photographs, both taken from the same offshore location in Harris Bay showing the changes that have occurred to Northwestern Glacier, KEFJ. Figure 5A shows the retreating terminus of Northwestern Glacier, in July 1909, extending to within ~1,500 ft (450 m) of its late-LIA maximum position. Figure 5B, taken in August 2004, shows that Northwestern Glacier has retreated out of the field of view. Ice-free Harris Bay and Northwestern Lagoon make up the foreground of the image.**

Figure 2a: USGS Photographic Library photograph by U.S. Grant
Figure 2b: USGS photograph by Bruce F. Molnia
Figure 3b: USGS photograph by Bruce F. Molnia
Figure 4a: USGS Photographic Library photograph by U.S. Grant
Figure 4b: USGS photograph by Bruce F. Molnia
Figure 5a: USGS Photographic Library photograph by U.S. Grant
Figure 5b: USGS photograph by Bruce F. Molnia

tion of the site, and bearing to the center of each photographic target. Details were determined with GPS receiver and compass. At each location a suite of digital images and/or color film photographs were made of the same geographic features displayed in the field of view of the historical photograph, often using lenses of different focal lengths. Where possible, larger fields of view were imaged so resulting images could be cropped to match the historic image. Many historical photographs were made with rotating lens, panoramic, or mapping cameras, typically with fields of view that exceed those of most modern normal or wide-angle lenses. Consequently, for some locations, overlapping, sequential photographs were obtained that could be digitally stitched together.

In Glacier Bay's upper East Arm, where glacier retreat has been continuous for more than two centuries, several locations from which the lead author photographed McBride, Riggs, and Muir Glaciers between 1976 and 1980 were revisited. Nearly all of these locations were under glacier ice prior to the 1970s. Hence, these photographs are the 'historical' photographs in this area.

For KEFJ, very few pre-1950 photographs exist. Less than 50, early twentieth century, ground and sea surface-based photographs have been located that show identifiable landscape features. Almost all depict glacier termini and related features. Except for a few postcards, all date from 1909 and were made by U.S. Grant and D.F. Higgins, university professors who worked as contract geologists for the USGS. Their photographs were found at the USGS Photographic Library. Several dozen were published with sketch maps that identified photograph sites and glacier termini *(Grant and Higgins 1911, 1913)*.

During the summers of 2004-2006, ~40 KEFJ locations were identified and revisited, using the same methodologies as in GLBA. Grant and Higgins' text and sketch maps were useful in narrowing down about 25% of the locations. At many KEFJ sites, twentieth century glacier retreat exceeded ~9-12 mi (15-20 km). Consequently, many glaciers in the 1909 photographs were no longer visible from the original photo locations. No cairns were found at any location.

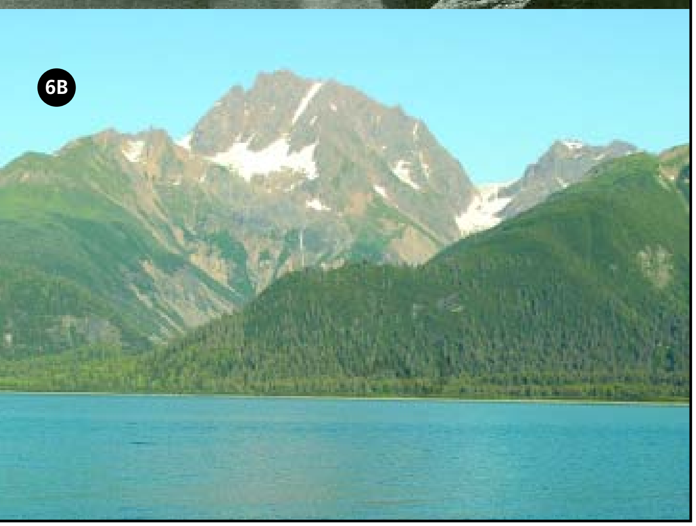
Following field work in both parks, new images and photographs were compared and contrasted with corresponding historical photographs to determine types and amounts of change, and to understand rates, timing, and mechanics of landscape evolution. Particular emphasis was placed on documenting the response of glaciers to changing climate and environment. In addition to the extracted information, the resulting photographic pairs provide striking visual documentation of the dynamic landscape evolution occurring in both parks.

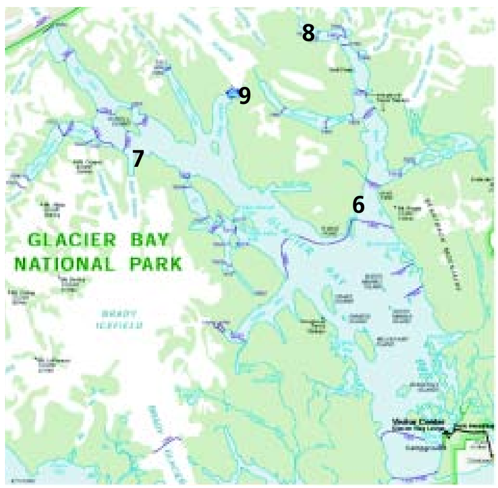
Results

Repeat photography provides significant insights into the post-LIA evolution of the landscapes of KEFJ and GLBA. For KEFJ, photographic evidence documents more than 80% of the post-LIA period. Information derived from the before and after pairs has been useful in documenting:

1) rapid influx of vegetation and the transformation from glacier till and bare bedrock to forest;
2) the post-1909 magnitude of retreat and thinning of Bear Glacier *(Figure 4);*
3) a similar thinning and retreat of Holgate Glacier and its former tributary, informally named Little Holgate Glacier;
4) the substantial retreat of Pedersen Glacier and the subsequent development of an extensive wetland *(Figure 3);*
5) the relatively small amount of change at Aialik Glacier;
6) the substantial post-1909 retreat of Northwestern Glacier resulting in the opening of Harris Bay and Northwestern Lagoon *(Figure 5);*
7) a similar substantial post-1909 retreat of McCarty Glacier resulting in the opening of McCarty Fiord *(Figures 1 and 2);* and
8) the transition from tidewater termini to land-based, stagnant or retreating, glacier termini at several locations including Yalik and Petrof Glaciers.

Visualizing Climate Change – Using Repeat Photography to Document the Impacts of Changing Climate on Glaciers and Landscapes





Location of paired images photographed in Glacier Bay National Park.

6 Figure 6. A pair of east-looking photographs, both taken from the same shoreline location on the west side of Muir Inlet, opposite Muir Point in GLBA. Figure 6A, taken in the late1890s, shows the terminus of Muir Glacier extending almost to the photo point and the absence of any identifiable vegetation. The August 2005 photograph (Figure 6B) documents the disappearance of Muir Glacier from the field of view. During the period between photographs, Muir Glacier has retreated ~15 mi (~25 km). Note the extensive vegetation.

7 Figure 7. A pair of south-looking photographs, both taken from the same hillside location near the mouth of Reid Inlet on the west side of the West Arm of Glacier Bay. Figure 7A shows the calving terminus of Reid Glacier extending almost to the mouth of Reid Inlet and the absence of any identifiable vegetation in June 1899. Figure 7B documents the retreat of Reid Glacier, almost out of the field of view, in September 2003. During the period between photographs, Reid Glacier retreated ~1.2 mi (~2 km). The spit of land that projects into Reid Inlet is part of an early twentieth century recessional moraine.

8 Figure 8. A pair of north-looking photographs, both taken from the same location in upper Muir Inlet showing changes that have occurred to the terminus of Muir Glacier, GLBA. Figure 8A shows the tidewater calving terminus of Muir Glacier extending across the entire field of view in July 1978. The height of the terminus above the fiord is ~165 ft (~50 m). Figure 8B, taken in September 2003, shows that the terminus of Muir Glacier has retreated from tidewater and is now terrestrial. Ice-cored recessional moraine and sediment deposits sit between the shoreline and the glacier terminus.

9 Figure 9. A pair of northwest-looking photographs, both taken from the same location, several hundred meters up a steep alluvial fan located in a side valley on the east side of Queen Inlet, showing the changes that have occurred to Carroll Glacier and upper Queen Inlet. Figure 9A, taken in August 1906, shows the calving terminus of Carroll Glacier sitting at the head of Queen Inlet. Small shrubs in the foreground are the only vegetation that is visible. Figure 9B, taken 98 years later on June 21, 2004, shows that the terminus of Carroll Glacier has changed to a stagnant, debris-covered glacier that has significantly thinned and retreated. The head of Queen Inlet has been filled by sediment. An examination of early twentieth century nautical charts suggests that the sediment fill exceeds ~400 ft (125 m). Note the trees on the hillside and the vegetation that is developing on the sediment fill.

Figure 6a: Glacier Bay National Park archive
Figure 6b: USGS photograph by Bruce F. Molnia
Figure 7a: USGS Photographic Library photograph by G.K. Gilbert
Figure 7b: USGS photograph by Bruce F. Molnia
Figure 8a: USGS photograph by Bruce F. Molnia
Figure 8b: USGS photograph by Bruce F. Molnia
Figure 9a: USGS Photo Library photograph by C.W. Wright
Figure 9b: USGS photograph by Bruce F. Molnia

For GLBA, photographic evidence documents approximately half of the 250 years of the post-LIA period. Information derived from the before and after pairs has been useful in documenting:

1) the rapid influx of vegetation and the transformation from glacier till and bare bedrock to forest;
2) the post-late-1880s timing and magnitude of glacier retreat in East Arm, a trend continuing to the present *(Figure 6);*
3) a similar continuous retreat of the glaciers in the Geikie and Hugh Miller Inlet areas of West Arm;
4) early-twentieth century retreat and subsequent variability of Reid and Lamplugh Glaciers *(Figure 7);*
5) early-twentieth century advances of Johns Hopkins and Grand Pacific Glaciers, followed by the continued advance of Johns Hopkins Glacier and the retreat and thinning of Grand Pacific Glacier;
6) decadal-scale fluctuations of smaller glaciers, such as hanging glaciers in Johns Hopkins Inlet, including Hoonah and Toyatte Glaciers;
7) transitions from tidewater termini to land-based, stagnant or retreating, debris-covered, glacier termini in a number of locations including Muir, Carroll, and Rendu Glaciers *(Figure 8);*
8) the filling of upper Queen Inlet with more than 400 ft (~125 m) of sediment *(Figure 9);*
9) the rapid erosion of fiord-wall moraine following ice retreat; and
10) the development of outwash and talus features at many locations.

Our goal has been to locate and acquire historical photographs that document this dynamic landscape evolution, to interpret these historical photographs to quantify and visualize the appearance of the landscape at the time they were made, to revisit locations from which historical photographs were made and duplicate the photographs, and to document changes at each location and provide written and visual products that depict the mechanics and magnitude of the changes that occurred during the intervening period of time. We believe that the images presented here document our success.

To download before and after photograph pairs:
http://nsidc.org/data/glacier_photo/special_collection.html

To view animated pairs that simulate time-lapse photography of landscape change:
http://www2.nature.nps.gov/geology/GLBA/glaciers.htm and http://www.oceanalaska.org/research/rptglacier.htm

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Photograph by Rebekah Helms