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A FIRE CYCLE MODEL BASED ON CLIMATE FOR THE OLYMPIC MOUNTAINS, WASHINGTON

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1. INTRODUCTION

Fire has been a significant ecological factor in the forests of the Olympic Mountains. Recent evidence includes large, lightning-caused fires as well as previously fire-scarred trees, silver snags created by fires, charcoal in soil, mosaic patterns of even-aged trees, and charred wood on the forest floor (Fonda and Bliss, 1969; Kuramoto and Bliss, 1970; Agee and Huff, 1980). Regional pollen profiles suggest that fire has repeatedly burned these areas over the last 10,000 years (Tsukada, et al., 1981).

Measuring the recent frequency of natural fire in a moist fire environment is difficult. Techniques such as counting multiple fire scars on a tree work well in dry environments where fire is frequent and of low intensity, but in the Olympic Mountains fire-scarred trees are not common because most trees are killed in fires; multiple scars are rare. Usually, some form of forest age-class analysis is used to estimate fire return intervals. The natural fire rotation (NFR) method calculates a fire cycle based on the time necessary to burn an area equal in size to the study area (Heinselman, 1973). Reconstruction of all past fire events is required, but is difficult because information is usually lost due to reburns of earlier fire events. Over the "rotation," some areas may burn twice and others not at all. Another method is to use only the present age-class distribution, which avoids the need for event reconstruction, and then assume a known statistical distribution applies to the current age classes. Van Wagner (1978) has used this method with success in boreal forests, assuming a negative exponential distribution of forest age classes. In order to use either method, considerable knowledge of forest age classes is necessary. Such data are not available within Olympic National Park (Figure 1), although Henderson and Peter (unpub. reports, Olympic National Forest, Olympia, Wa.) have compiled age class data on the surrounding Olympic National Forest. A modeling approach to determine fire rotations was therefore employed. The objectives of the model were to simulate modern lightning fire activity using modern climatic and fire information and, once verified, to use the model to interpret past fire within the park.

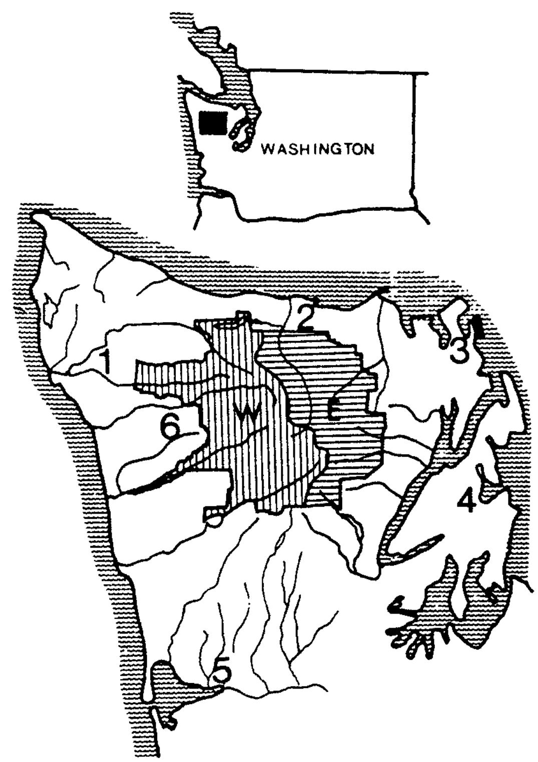

Fig. 1. *Location of central portion of Olympic National Park, Washington: West and east sides. Key: 1, Forks; 2, Port Angeles; 3, Port Townsend; 4, Bremerton; 5, Aberdeen; 6, Clearwater.*

2. MODEL CONCEPT

The model is based on a Monte Carlo approach using park lightning fire activity and local weather records back to the early 1900s. These data have been previously analyzed by Pickford, et al. (1980) and Huff and Agee (1980). Large ($\geq$1 ha) lightning fires were associated with several months of drought before the fire, short-term dry spells before ignition, thunderstorm activity which served as an ignition source, and an east wind synoptic weather type, associated with low relative humidity and in some locations strong winds.

The behavior of a fire is a function of fuels, weather, and topography. Steep, south-facing slopes are most likely to burn, while major river valleys and up-down slope riparian zones have acted as fire barriers. The fire size equation is based on weather variables, using actual fire event sizes and correlating them to dry periods before and after ignition. The resulting equation is therefore applicable only to the Olympics, because fire event size is related to the specific fuel conditions and topographic barriers of these mountains.

The flow diagram of the model (Figure 2) is relatively simple. The program operates by incrementing twelve 10-day fire periods (June through September) for each of N years. Within each year, a random selection of yearly drought intensity is made, and the first period is incremented. If no thunderstorm occurs, the next period is incremented. If in any period a thunderstorm occurs, then a probability of ignition based on short-term drought is calculated. If no ignition occurs, the next period is incremented. If ignition is successful a significant (>1 ha) fire event will occur only if an east wind condition occurs before significant (0.25 cm) precipitation occurs. If the fire event meets all conditions, its size is determined as a function of drought intensity. Multiple ignitions from the same thunderstorm are treated as one occurrence or "event." Significant fire activity within periods and years is recorded. At the end of the designated number of years, the total time period is divided by the proportion of total area burned over the period to calculate the fire rotation.

The model was applied to seven different situations on the east and west sides of the park. The first situation was the unmanaged natural fire scenario assuming no fire suppression. Because the actual modern area burned includes the effect of fire suppression, a second version was run, eliminating the effects of fire suppression. This run was used to verify the model against actual modern area burned. Other runs included increasing the probability of a drought year, thunderstorms, east winds, and combinations of increased drought or thunderstorms with increased east wind probability.

Long-Term Drought

Drought was defined as below-average precipitation. Precipitation records from three stations on the Olympic Peninsula were used to construct the cumulative probability of the number of previous drought years to any current year. Long-term annual averages from Aberdeen (1893-1980), Bremerton (1900-1980), and Port Townsend (1911-1980) were used. For each year of record, above or below average values were noted. For the three stations, 50, 47, and 51 percent of the years were below average, so "drought" occurred 50 percent of the time. Based on the runs of drought years in the data from the three stations, the cumulative probability of one or more years of drought was calculated (Figure 3). In the model, once a new year is incremented, a random number generator is used to choose the number of drought years previous to the current year.

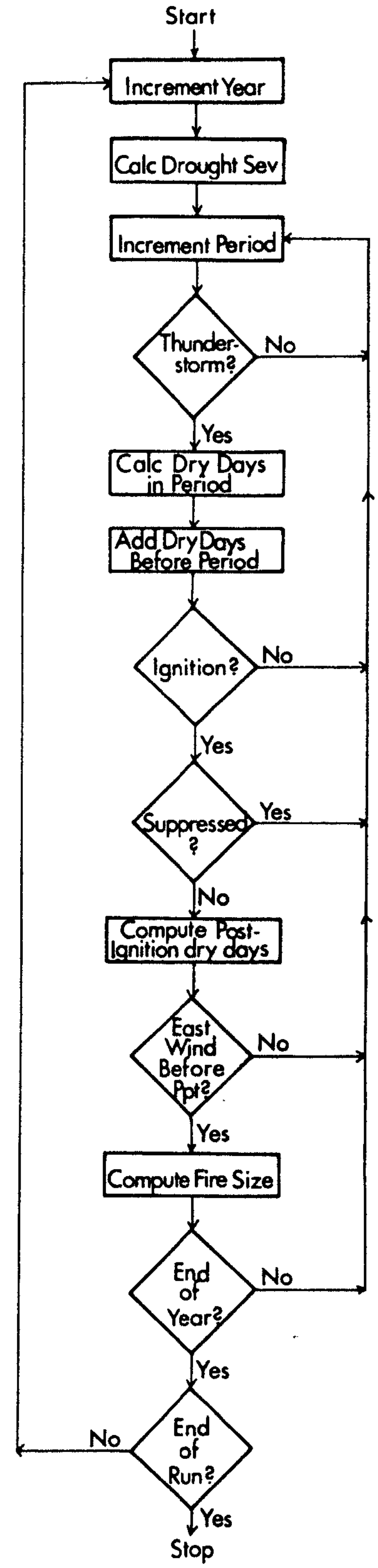

Fig. 2. *Flow diagram of the fire cycle model.*

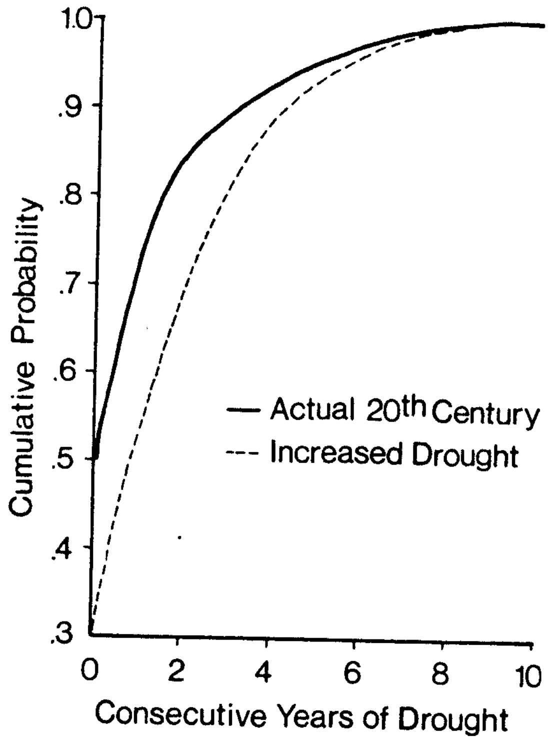

Fig. 3. *Cumulative probability of below-normal annual precipitation (drought) for the actual record and under the assumption of increased drought.*

Short-Term Drought

The presence and absence of rain in 10-day increments is determined for the period June 1 - September 30. Rainfall probabilities were estimated using 11 to 30-year records from Munger (1925) for local stations. Westside stations used were Clearwater and Forks; east-side stations were Port Angeles, Bremerton, and Port Townsend. Munger's probability class of "light rain" (trace to .5 cm) was equally divided between the model classes of significant precipitation (≥.25 cm) and no significant precipitation (<.25 cm).

Station probabilities were averaged and extended earlier into June and later in September than reported by Munger; the extensions were based on extrapolating known probabilities out to the beginning and end of the fire season. The model can then calculate rainfall probability within a period (Table 1) and, using the values of earlier and later periods, calculate the number of dry days before and after any potential ignition.

Thunderstorm and Ignition Probability

The probability of a thunderstorm by 10-day periods was calculated using data from Pickford, et al. (1980). The period 1945-63 was used to determine total thunderstorms and probability of a thunderstorm by 10-day periods from June through September (Table 1). The probability of ignition, given a thunderstorm, was calculated as a function of days since significant rainfall using the equation Y = 0.0611 + 0.0246 (no. of dry days), $r^2 = 0.69$ (Pickford, et al., 1980), area-weighted for the west (0.58) and east (0.42) sides of the park.

Table 1. Model inputs for significant precipitation, east wind, and thunderstorm probabilities.

Date	Period	Sig. Ppt. West	Sig. Ppt. East	East Wind	Thunder-storm
Jun 1-10	1	.95	.92	.16	.153
Jun 11-20	2	.95	.82	.16	.105
Jun 21-30	3	.90	.70	.16	.105
Jul 1-10	4	.66	.56	.33	.253
Jul 11-20	5	.58	.56	.33	.279
Jul 21-31	6	.60	.38	.33	.168
Aug 1-10	7	.44	.35	.23	.200
Aug 11-20	8	.68	.57	.23	.289
Aug 21-31	9	.66	.57	.23	.342
Sep 1-10	10	.83	.69	.34	.168
Sep 11-20	11	.90	.82	.34	.142
Sep 21-30	12	.95	.92	.34	.084

East Wind Probability

When an ignition occurs, the probability of a large fire event is assumed to depend on the occurrence of an east wind before significant rainfall develops. East wind probabilities were gathered from a 10-year record from Schroeder (1969) based on average occurrence and average duration of east winds for the months of June through September. Because means were monthly, the same probabilities were assigned within each of the three periods in a month (Table 1). The Pacific High generated most of the east winds, but in September the Northwest Canadian High also causes east winds, increasing September probabilities above those of other months.

Fire Size

The size of large lightning fire events in Olympic National Park was highly correlated to the number of days after ignition without precipitation (r = 0.91) and number of previous years of below-normal rainfall (r = 0.93) (Huff and Agee, 1980). These variables were used in a multiple regression (adjusted $r^2 = 0.83$) to predict fire event size using data from park fire records:

$$\text{SIZE (ha)} = 42.81 + 9.00\ (\text{post dry days}) + 183.72\ (\text{no. of drought years})$$

Although climatic parameters are used to predict event size, fuels and topography have historically acted as natural fire barriers, so their effect is integrated into the fire event size equation. Large fire events (>20 ha) were used to develop the relation to climate because these have been least affected by fire suppression.

Computing Fire Rotations

The program runs for a predetermined number of years, summing area burned by month and year over time. Land areas used for westside and eastside areas were 175,000 ha and 125,000 ha, including forest and tree clump/meadow types, but excluding ice, rock, and alpine meadows. The formula to calculate natural fire rotation (NFR) in years is:

$$NFR = \frac{\text{Time Period}}{\text{Area Burned/Total Area}}$$

The NFR is calculated at the end of a model run.

Effect of Fire Suppression

The impact of fire suppression was estimated by comparing actual fire records to data generated by the natural fire run of the model, which assumes no fire suppression by humans. The total number of large ignition events in the model was compared to the total number of ignition events in the model: 45.9 percent were large (>1 ha). Actual fire records showed that the number of large fire events was 22 percent of the total over the 1916-1981 period: 34 percent before 1950, and 8 percent since 1950. Suppression efficiency of large fire events was assumed to be the difference between actual and expected: (45.9-22.0)/45.9, or 52.2 percent. This figure was inserted into the model for the fire suppression run, and in theory should produce fire cycles comparable to the actual record.

Other Program Options

The impact of increased thunderstorms, east wind, or drought was estimated by changing input values for those variables (Table 2). East wind probabilities were increased by 50 percent. Drought was increased by raising long-term drought probability (Figure 3) and decreasing summer precipitation (Table 2). Other levels could have been chosen for these variables to illustrate less or more severe changes.

Table 2. Model inputs for increased drought, east wind, and thunderstorm occurrence. Increased drought includes decreasing summer precipitation plus increased probability of annual drought (see Figure 3).

Period	Sig. Rainfall Prob. West	Sig. Rainfall Prob. East	East Wind	Thunderstorm
1	.75	.72	.24	.20
2	.75	.62	.24	.25
3	.70	.50	.24	.30
4	.46	.36	.50	.35
5	.38	.36	.50	.40
6	.40	.18	.50	.40
7	.24	.15	.35	.40
8	.48	.37	.35	.40
9	.46	.37	.35	.35
10	.63	.49	.51	.30
11	.70	.62	.51	.25
12	.75	.72	.51	.20

3. RESULTS

Fire Cycles

Long-time periods were necessary in the model to produce average fire cycles approaching true expected values. For all sample runs, three 10,000 year runs were averaged to compute fire cycles (Table 3).

Table 3. Average fire cycles for the Olympic fire model. Each model average is the mean of three 10,000 year runs. The actual 1916-81 record is in parentheses.

Model Assumptions	West-side	East-side	Whole Park
Actual record (1916-81)	(13020)	(4195)	(9312)
Natural fire cycle	4110	2675	3505
Fire suppression	8520	5350	7190
Inc. thunderstorms	2590	1620	2180
Increased east wind	3080	2005	2630
Increased drought	1410	860	1180
Inc. thunderstorm/ east wind	1900	1240	1625
Increased drought/ east wind	1085	685	915

The "natural" fire cycle, based on twentieth century weather, was longer on the west than the east side of the park; both exceeded socially meaningful time spans. These figures suggest that even if fires were allowed to burn, burned area would be small. The fire suppression cycle was about twice as long as the "natural" cycle; this cycle was compared to the actual fire activity in the park. The parkwide model fire cycle was 77 percent of the actual fire cycle (1916-1981). The westside model fire cycle was about 65 percent of actual, while the eastside model fire cycle was 130 percent of actual.

The other model runs increased the probabilities of ignition and/or increased event size. Fire cycles in these situations were therefore less than the "natural" fire cycle. The model was most sensitive to increased drought, because the fire event size was tied to pre-fire drought and post-fire rain-free weather. Drought increased both the number and average size of fire events. East winds and thunderstorms, when probabilities were increased, affected numbers of large fire events but not average event size.

The only fire cycles below 1000 years occurred on the east side of the park and were associated with increased drought. For the park as a whole, increased drought plus east winds were required to bring the fire cycle below 1000 years. Other types of probabilities than those in Table 2 and Figure 3 could have been used in the model; the levels selected were in all cases judged to be significant increases in the climatic factors.

Seasonal Occurrence

The seasonal distribution of actual and simulated large fire events in the park were very close (Figure 4). Because the actual record includes fire suppression, it was compared to the fire suppression model. All runs of the model assume no large fire events in May and October, so all possible fires are restricted to the period June - September. Actual large fire event occurrence has been limited to July - September.

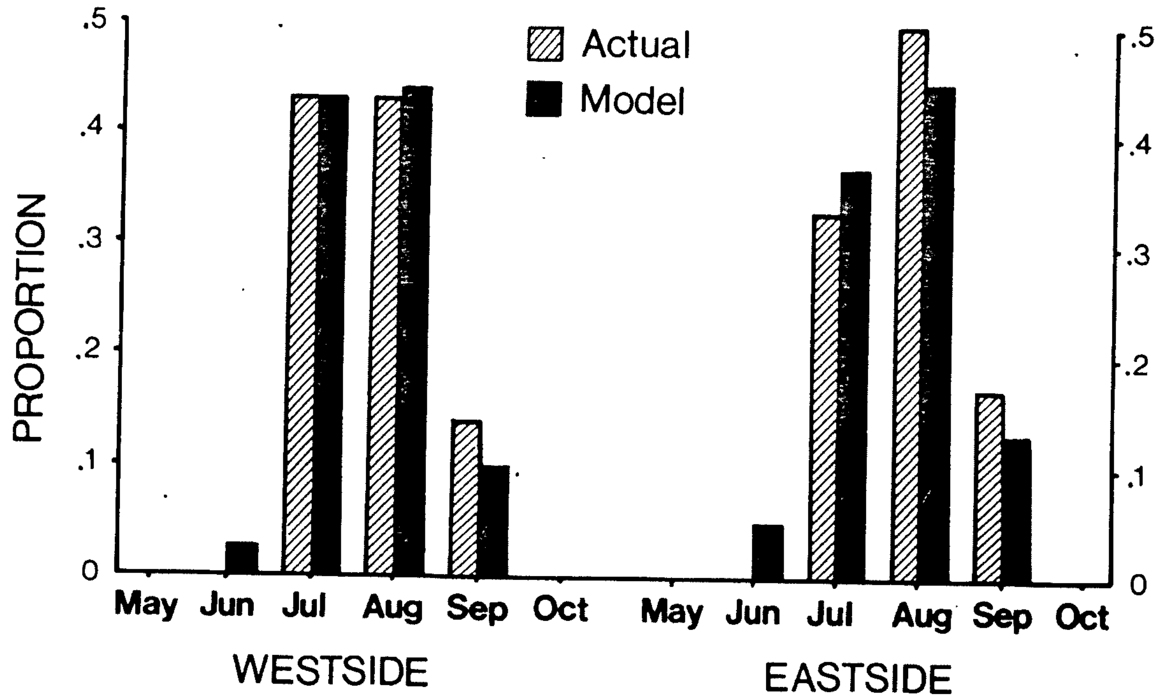

Fig. 4. *Seasonal distribution of large fire event occurrence for the west and east sides of the park.*

A chi-square analysis on the June - September proportions showed no significant difference between the actual and simulated distributions for either the westside or eastside models.

4. DISCUSSION

Model validation was only partially possible, as the actual fire record used initial model output to estimate suppression efficiency, and there is no independent data set available for this site-specific model. In such a moist forest environment, the actual fire data set is so small compared to the length of the fire cycle (60 versus 7000 years) that only 1 percent of the estimated fire cycle is available for model validation.

The parkwide model provided a closer estimate of the actual (1916-81) fire cycle (77 percent) than the westside (65 percent) or eastside 130 percent) models. This is likely due to the artificial division of the park into two sides; the generally radial drainage pattern is not clearly separated into east and west halves.

There are several reasonable explanations for the difference between the simulated and actual fire cycles. The first is that the model, simple as it is, is too crude to be more precise. In most cases, data covered a period of one or two decades only. A second reason is that given the very long fire cycles, a 65-year real record may be too short to produce a true mean fire cycle. To evaluate this second possibility, the model output was segregated into 60-year increments (roughly the length of actual record). With an assumption that fire cycles calculated for each increment were normally distributed, the coefficient of variation was 98 percent. Any single 60-year period is a poor estimate of long fire cycles, even given the model assumption of long-term stable climate. The model prediction for a parkwide fire cycle of 7190 years may be reasonably close to the true cycle, even though it is 77 percent of the actual 1916-1981 mean.

The model closely approximates the seasonality of fire events. Both the eastside and westside models show large lightning fire events in June, although such activity is not common. Given the short historical record, future large fire events in June should be expected to occur.

The effect of fire suppression has been to catch fires while they are small and before east winds develop. The model predicts that 45 percent of ignitions will develop into large fire events (>1 ha) in the absence of suppression. With suppression, the actual percentage has been less, suggesting that fire suppression has reduced area burned. The model predicts an average "saving" of 45 ha per year, or 2950 ha over 65 years of fire suppression. Due to more effective fire suppression in recent years, future area "saved" per year should increase as long as the fire suppression policy endures. Even so, the impact to date is negligible over a 300,000 ha area, particularly when contrasted to the ecological changes due to fire suppression in much drier forest environments with frequent fire cycles (Parsons and DeBenedetti, 1979).

The "natural" and fire suppression fire cycles are far too long to account for known past fire activity in the park. While precise on-the-ground fire rotations have not been computed, most stands in the park are first-generation post-fire stands and are below 750 years of age. It is possible that the climatic variables of the model, which are based on twentieth century records, may have differed in past centuries. At nearby Mount Rainier National Park, Hemstrom and Franklin (1982) documented fire rotations through aging all forests in the park. They found the twentieth century fire rotation to exceed 2000 years, while the average for the past 750 years has been about 450. They associated past large fire events with drought episodes as revealed in tree rings. Some centuries had a lot of fire activity separated by other centuries with very little.

The model runs for increased drought produce what appear to be the most reasonable fire cycles for the park. However, cursory examination of tree-rings suggests that significantly increased drought of that magnitude has not occurred for the necessary decades to centuries which the model assumes. Furthermore, the forest age-class data available appear to indicate several major fire events (ca. 1230, ca. 1480, ca. 1650). These may have been the result of very short-term but simultaneous increases in two or more of the climatic factors associated with large fire events.

5. CONCLUSIONS

a. The major climatic variables affecting large naturally occurring fire events in Olympic National Park are short to long-term drought, presence of thunderstorms, and east winds. The model using these variables reasonably approximates both fire cycles and seasonal distribution of large fire events.

b. Fire suppression has affected the area burned by fire in the twentieth century by keeping fires small. The magnitude of this impact is negligible compared to fire suppresion impacts in forests with very frequent fire cycles.

c. The fire activity of this century underestimates past fire activity in the park, even when effects of fire suppression are eliminated.

d. Increased drought in the model produces fire cycles that appear more realistic in terms of ground evidence of past fires. However, drought of such magnitude over long periods of time does not seem likely, and several major fire events appear to be responsible for much of the past burned area. Unusually high short-term increases in two or more fire climate factors may be responsible.

LITERATURE CITED

Agee, J.K. and M.H. Huff. 1980. First year ecological effects of the Hoh Fire, Olympic Mountains, Washington. Pp. 175-181 in Sixth Conf. Fire and Forest Meteor. Soc. Amer. For., Washington, D.C. 304 pp.

Fonda, R.W. and L.C. Bliss. 1969. Forest vegetation of the montane and subalpine zones, Olympic Mountains, Washington. Ecol. Monog. 39:271-301.

Heinselman, M. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quater. Res. 3(3):329-382.

Hemstrom, M.A. and J.F. Franklin. 1982. Fire and other disturbances of the forests in Mount Rainier National Park. Quater. Res. 18:32-51.

Huff, M.H. and J.K. Agee. 1980. Characteristics of large lightning fires in the Olympic Mountains, Washington. Pp 117-123, in Sixth Conf. Fire and Forest Meteor. Soc. Amer. For., Wash., D.C. 304 pp.

Kuramoto, R.T. and L.C. Bliss. 1970. Ecology of subalpine meadows in the Olympic Mountains, Washington. Ecol. Monog. 40:317-347.

Munger, T.T. 1925. Rainfall probability during the fire season in western Washington and Oregon. Monthly Weather Review, Sept. 1925, 53:394-397.

Parsons, D.J. and S.H. DeBenedetti. 1979. Impact of fire suppression on a mixed-conifer forest. Forest Ecol. and Mgt. 2:21-33.

Pickford, S.G., G. Fahnestock, and R. Ottmar. 1980. Weather, fuel, and lightning fires in Olympic National Park. Northwest Sci. 54(2): 92-105.

Schroeder, M.J. 1969. Critical fire weather patterns in the conterminous United States. U.S. Dept. Commerce, ESSA Tech. Rpt. WB-8. Govt. Print. Off., Wash., D.C. 31 pp.

Tsukada, M., S. Sugita, and D.M. Hibbert. 1981. Paleoecology in the Pacific Northwest. I. Late Quaternary vegetation and climate. Verh. Internat. Verein. Limnol. 21:730-737.

VanWagner, C.W. 1978. Age-class distribution and the forest fire cycle. Can. J. For. Res. 8:220-227.

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CHARACTERISTICS OF LARGE LIGHTNING FIRES IN THE OLYMPIC MOUNTAINS, WASHINGTON

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INTRODUCTION

The steep mountains and lush glaciated valleys of Olympic National Park, located in western Washington, are subjected to a wide diversity of climatic conditions. Mount Olympus, 2,426 m in elevation, is the wettest location in the continental United States, with approximately 500 cm of precipitation per year. In the northeastern section of Olympic National Park, where a rain shadow exists, precipitation is less than 50 cm per year. Throughout Olympic National Park, October through April are the wettest months. Forest fires tend to occur in July, August, and early September, when drought conditions persist during the summer months.

The role and occurrence of natural and man-caused fires in Olympic National Park were assessed by Pickford et al. (1977). They obtained weather records from recording stations on the Olympic Peninsula to cross-correlate them with fire occurrence and determine fire occurrence probability under various weather patterns. Records indicate that large lightning fires are infrequent and occur under unusual weather conditions.

Since 1916, a total of 2,984 ha burned in Olympic National Park. Eighty-three percent of the total were burned by lightning fires. Most natural fires in Olympic National Park are less than 0.1 ha in size (Pickford et al. 1977); infrequent but large lightning fires, such as the 1978 Hoh Fire which burned 492 ha, account for most of the burned area.

The interaction of fuels, weather, and topography determines the spread and intensity of wildland forest fires. In Olympic National Park, most fires occur on rocky and precipitous south-facing slopes. Orographic storms, important for the ignition of fuels, produce wildland fires only under certain conditions. Peak thunderstorm activity occurred in 1946, 1949, 1953, and 1958, yet no significant fires ensued even though a high frequency of ignition was present. Fire occurrence may be determined by fuel moisture as a function of time since last significant precipitation (Pickford et al. 1977).

Infrequent large lightning fires in relatively moist forests, such as those in Olympic National Park, could result from long periods of drought under unusual climatic conditions. The objective of this study is to describe climatic characteristics of large lightning fires in Olympic National Park. The study hypothesis is: climatic conditions of seasons when large lightning fires occur differ from the climatic conditions of seasons without large lightning fires. The study examines the significance of the following variables:

1. Number of days without significant rainfall before a large lightning fire.
2. Number of days without significant rainfall after a large lightning fire.
3. Number of consecutive months of below normal rainfall before a large lightning fire.
4. Number of months of below normal rainfall before a large lightning fire allowing for one month above normal rainfall.
5. Number of consecutive years of below normal rainfall before a large lightning fire.

This study also examines the relation of the climatic variables to the number of hectares burned and discusses the 1978 Hoh Fire.

METHODS

Precipitation data from 1922 - 1978 was gathered for nine weather stations on the periphery of Olympic National Park (Figure 1).

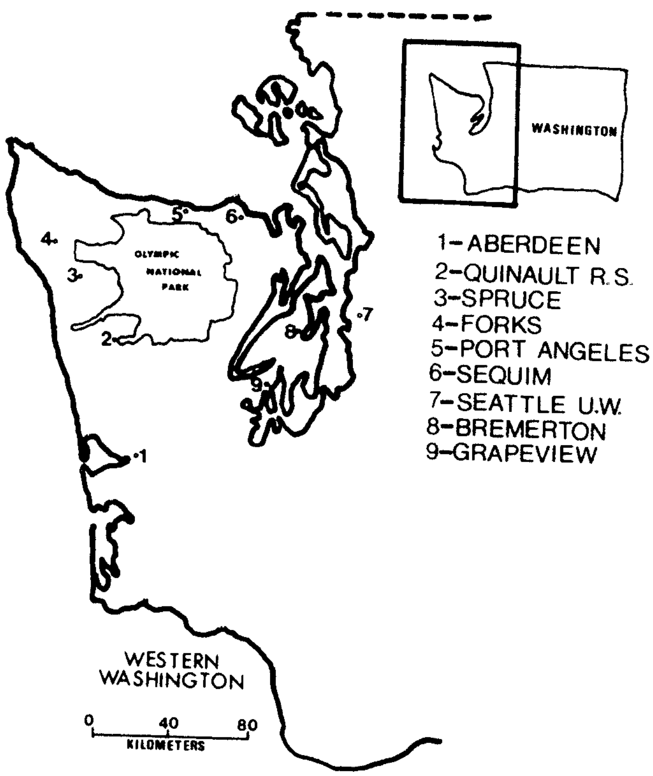

Figure 1. Weather stations on the Olympic Peninsula from which data were used.

Climatological records for Washington State were obtained from the Environmental Data Service, National Oceanic and Atmospheric Administration, Department of Commerce. A maximum of seven stations were used in the data analysis. Spruce and Seattle (Univ. of Washington) served as alternates when information from other stations was unavailable. The dates of large lightning fires were examined for the five climatic factors under investigation. The records for each date for the weather stations were averaged together, since the means reflect regional climatic variations better than records from individual stations (Fritts 1976, Brubaker 1980). Only the means were employed in the data analysis. The five climatic factors of these large lightning fires were then compared to the same climatic factors for a simulated fire date in a non-lightning fire year. The simulated fire season of July 12th to September 11th was determined by the fourteen large lightning fires in Olympic National Park from 1916 - 1978. Within a stratified random sample fourteen fire dates were simulated in non-lightning fire years. Six fires in July and August plus two in September were chosen to match the natural, large lightning fire occurrence in the park. The IRANDOM program from Minitab II (Ryan et al. 1976) computed random numbers representing the day and year for a simulated fire date.

Assumptions of normality and homogeneous variances were examined by plotting data points against rankit values, and Bartlett's test for homogeneity of variances (Sokal and Rohlf 1969). Data sets not meeting these assumptions were transformed by natural logarithms. Analysis of variance was employed to compare the mean climatic variables from large lightning fires to simulated fires. Correlation analysis evaluated the relationship between climatic variables and area burned from large lightning fires.

The following constraints and assumptions were developed for data collection and analysis:

1. Different aspects of precipitation data are the only variables investigated in this study.
2. A large lightning fire is defined as a fire greater than 0.5 ha in size. Large lightning fires are the only natural fires used in this study.
3. Individual fire records were not examined for suppression activities; however, the influence of man on the size of lightning fires at Olympic National Park, once they are larger than 0.5 ha, is thought to have been minimal even though suppression has been vigorously pursued.
4. Simulated fires were randomly chosen between 1925 - 1976. A simulated fire could not occur in a lightning fire year.
5. A climatic variable is a calculated mean from all weather stations for each fire. Mean precipitation values gathered from several reporting stations are an accurate representation of major weather patterns moving over the Olympic Peninsula.
6. Significant rainfall is defined as greater than or equal to 0.25 cm.
7. The number of months and years of below normal rainfall does not include the month and year of the fire respectively.
8. The number of consecutive days without precipitation after a lightning or simulated fire includes the day of the fire and the first day of significant rainfall.
9. The number of consecutive days without precipitation before a lightning or simulated fire includes the last day of significant rainfall before ignition, but does not include the day of the fire.
10. For statistical purposes all lightning fires within 31 days of a previous lightning fire were considered part of the first fire. Therefore the first ignition was

used as the fire date in data collection.

11. A simulated fire did not occur on a day of significant rainfall at more than one recording station. (On the ignition date of large lightning fires rarely did any stations report significant rainfall.)

12. The number of hectares burned for a lightning fire date is the total hectares burned by all ignitions on that date.

RESULTS

The ranges, grand means, and standard deviations of the climatic variables for large lightning fires and simulated fires are shown in Table 1. Analysis of variance of climatic variables showed that the number of consecutive days without significant precipitation and consecutive months of below normal rainfall before a large lightning fire are significantly different from a simulated fire (Table 2). All other climatic comparisons were not significantly different at alpha = 0.05.

Correlation analysis between the size of large lightning fires and the climatic factors showed if relationships exist between precipitation and large lightning fires (Table 2). The analysis was performed on two data groups, lightning fires larger than 0.5 ha and larger than 50 ha. No strong correlations existed with the 0.5 ha set but for the 50 ha and larger set, correlations above 0.9 were obtained between area burned and (a) number of days after the fire without rain and (b) number of years of below normal precipitation.

Table 2. Analysis of variance of climatic variables for simulated and large lightning fires (df 1,26) plus correlation of area burned and climatic variables.

Climatic Variables	F-ratio	Fires >0.5 ha r	Fires >50 ha r
# days before fire without rain	6.57**	-0.11	-0.63
# days after fire without rain	0.00	0.42	0.91
# consecutive months below normal Ppt.	7.20**	-0.16	-0.44
# consecutive months below normal Ppt. allowing one above	2.95	-0.04	-0.33
# years below normal rainfall	3.48	0.14	0.93

**Significant at alpha = 0.05

Table 1. The grand mean, range of means, and standard deviation of five climatic characteristics for simulated fires, large lightning fires, and the 1978 Hoh Fire in Olympic National Park.

Climatic Variable	Simulated Fires				Large Lightning Fires				Hoh Fire
	n	$\bar{\bar{x}}$	Range	s.d.	n	$\bar{\bar{x}}$	Range	s.d.	x
# days before ignition without rain	14	14.76	2.29-27.57	7.47	14	21.84	6.14-38.86	7.10	24.29
# days after ignition without rain	14	14.65	2.43-59.43	14.85	14	13.82	2.43-38.43	9.85	2.43
# consecutive months below normal rainfall	14	0.82	0.00- 2.43	0.72	14	1.90	0.00- 4.43	1.31	0.86
# consecutive months below normal rainfall allowing one above	14	3.22	1.57- 6.86	1.24	14	4.32	1.74- 9.60	2.04	2.14
# years below normal rainfall	14	0.85	0.00- 2.14	0.85	14	1.65	0.00- 5.29	1.37	1.14

DISCUSSION

Large Lightning Fires Since 1916

The statistical analysis indicated that some climatic variables of large lightning fires differ from climatic variables of years without large lightning fires. An obvious factor influencing the growth of fires in the Pacific Northwest is the number of days after ignition without significant precipitation. However, in this study, no significant difference in that variable existed between large lightning fires and randomly chosen dates: both averaged around fourteen days without rain. After a lightning ignition, this is more than enough time to develop a fire larger than 0.5 ha. Therefore this climatic factor does little to characterize the occurrence of large lightning fires in Olympic National Park.

Pickford et al. (1977) indicated that all lightning storms in Olympic National Park had started fires when no significant precipitation occurred 28 days or more before a thunderstorm. The importance of lack of precipitation is also observed in this study; the number of consecutive days without significant rainfall before large lightning fires is significantly different from simulated fires.

The number of months of consecutive below normal rainfall appears to be a most significant climatic variable. The other long-term climatic variables, the number of consecutive months allowing for one month above normal and the number of consecutive years of below normal precipitation before a large lightning fire, are significantly different at alpha = 0.1. This suggests that long periods of below normal precipitation could strongly influence large lightning fire occurrence in Olympic National Park.

For the total set of fires larger than 0.5 ha, no strong relationship exists between size and any of the climatic variables. Scattergrams showed that the small-sized fires (0.5 - 10 ha) had climatic variability. However, a subset of lightning fires larger than 50 ha showed a substantial relationship with two climatic variables: the number of consecutive days without significant precipitation after a large lightning fire and the number of consecutive years of below normal rainfall. Certainly, the lack of precipitation after a fire will enhance the size of a fire. The high correlation between the size of the fire and the number of years of below normal rainfall ($r = 0.93$) demonstrates that long-term climatic anomalies may also augment large fires in Olympic National Park.

The Hoh Fire

The climate of the Hoh Fire was quite similar to that of past large lightning fires in the Olympic Mountains. The climatic variable means were not significantly different from those of fires greater than 0.5 ha or greater than 50 ha. The number of consecutive days without precipitation before ignition was longer for the Hoh Fire than the overall mean, but the other climatic statistics were below the associated mean values for past large fires.

The Hoh Fire occurred in the second consecutive below normal year for precipitation. At the Hoh Ranger Station, the weather station nearest the fire, both 1977 and 1978 were below normal years for precipitation, though 1977 was only slightly below normal (Yanish, personal communication, 11/5/79). Cumulative departures from normal precipitation, set at zero at the beginning of the 1978 Water Year, are shown for several Olympic Peninsula weather stations in Figure 2. The water year started with a spread of values indicating above and below normal precipitation until January. After that time, all stations recorded a severe four-month drought. The largest departures from normal (Forks, Quillayute, Hoh Ranger Station) were found on the western peninsula which is usually the wettest area. May and June were relatively average months, although average rainfall is beginning to fall to low levels by this time of year. July tended to be below normal again, especially at the western stations. By August 1, 1978, the Hoh Ranger Station was showing a deficit of -47.52 cm (-18.71 in.), or 14 percent of average annual precipitation.

The significance of drought to fire behavior is that it affects the moisture content of live fuels and larger woody dead fuels. Decreased moisture in such fuels may cause them to be a heat source rather than a heat sink under extreme short-term fire weather conditions. This is the effect that drought had on the behavior of the Hoh Fire.

Short-term weather affecting the Hoh Fire is shown in Figures 3 - 5. The period July 26 - 27 was characterized by a thunderstorm that increased large dead fuel moistures and decreased fire danger. This thunderstorm ignited the Hoh Fire, which apparently smoldered almost two weeks while large dead fuel moistures decreased and fire behavior components/index increased. Beginning on Friday, August 4, a synoptic weather pattern characteristic of high fire danger in western Washington began to develop (Figure 5). This Pacific High pattern (Schroeder 1969) occurs when a portion of the Pacific High cell moves inland and low pressure exists at or off the coast. The east-west pressure gradient creates winds from the east with high temperatures and low relative humidities.

On August 7, smoke was reported from the Hoh Fire, as the Pacific High was moving into British Columbia. Low relative humidities through the night encouraged the spread of the fire in exceedingly rough terrain. The NFDRS rating values (Deeming et al. 1977) reached extreme high/low values during this period. By August 9, most of the area enveloped by the final fire perimeter had been burned. For these weather conditions, fuel and topographic barriers had been reached on all sides of the fire, and westerly flow on August 10 brought rain to the area. The period August 10 - 20 was characterized by increasing fuel moistures and decreased fire danger.

CONCLUSIONS

The following are average climatic characteristics of large natural fires in Olympic National Park.

1. Two years of below normal rainfall before ignition.
2. Below normal rainfall four of the five previous months before ignition.
3. Two consecutive months of below normal rainfall before ignition.

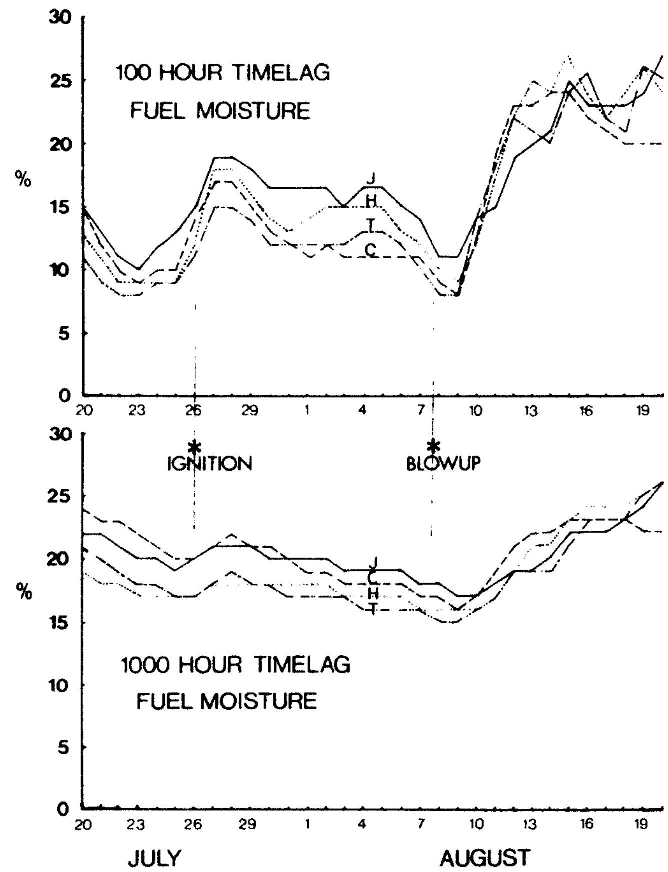

Figure 3. Large dead fuel moisture before, during, and after the Hoh Fire. Stations are: J=Jefferson, H=Humptulips, T=Tom Creek, C=Cougar Ridge.

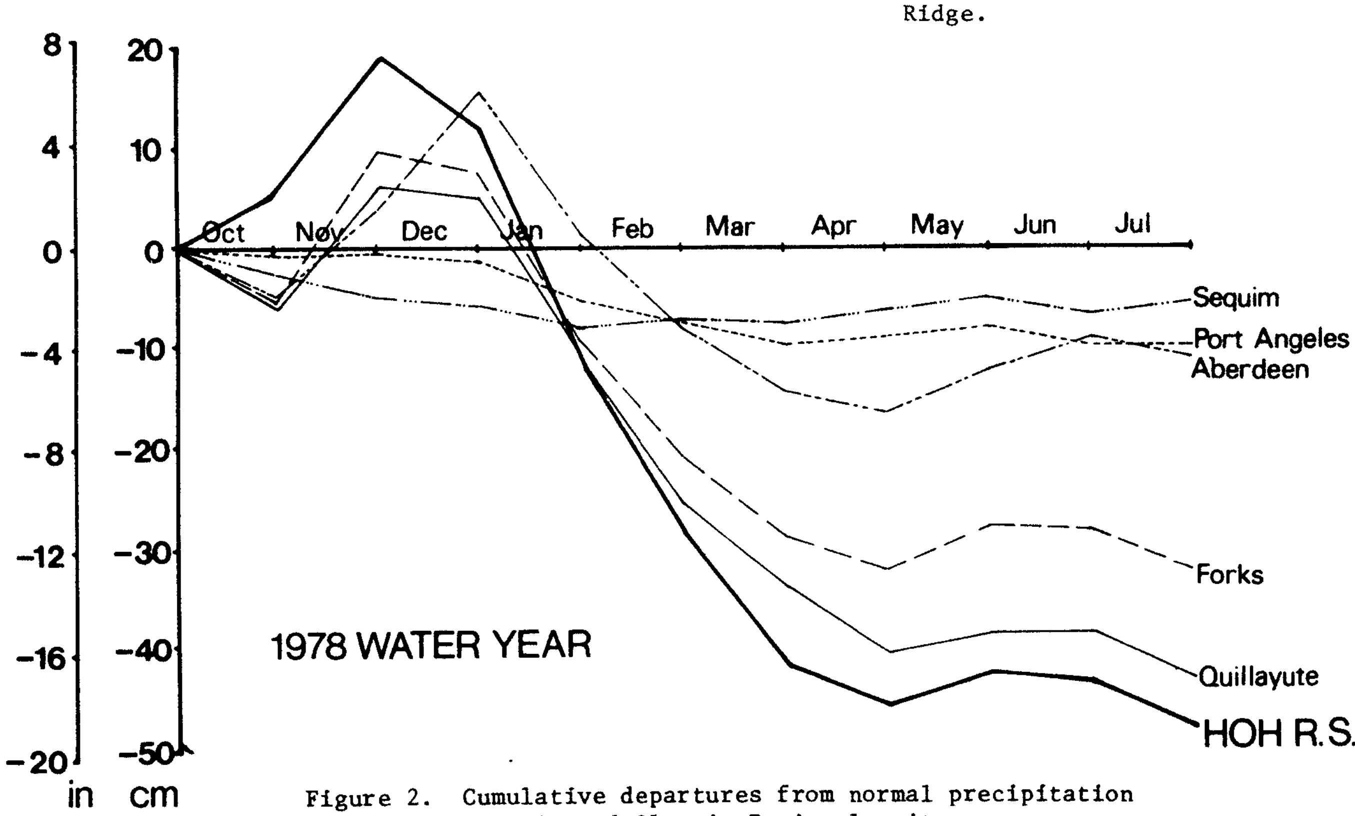

Figure 2. Cumulative departures from normal precipitation at selected Olympic Peninsula sites.

4. Twenty-two consecutive days without significant precipitation before ignition.

5. Fourteen consecutive days without significant precipitation after ignition.

6. Consecutive months of below normal rainfall and consecutive days without significant precipitation before ignition is significantly different from conditions in non-fire years.

7. Consecutive days without significant precipitation after ignition and consecutive years of below normal rainfall are highly correlated with the size of lightning fires larger than 50 ha.

The climate of the 1978 Hoh Fire was similar to these large fires of recent decades. Climate played a large role in creating conditions under which ignition and spread were possible and under which the fire was largely extinguished.

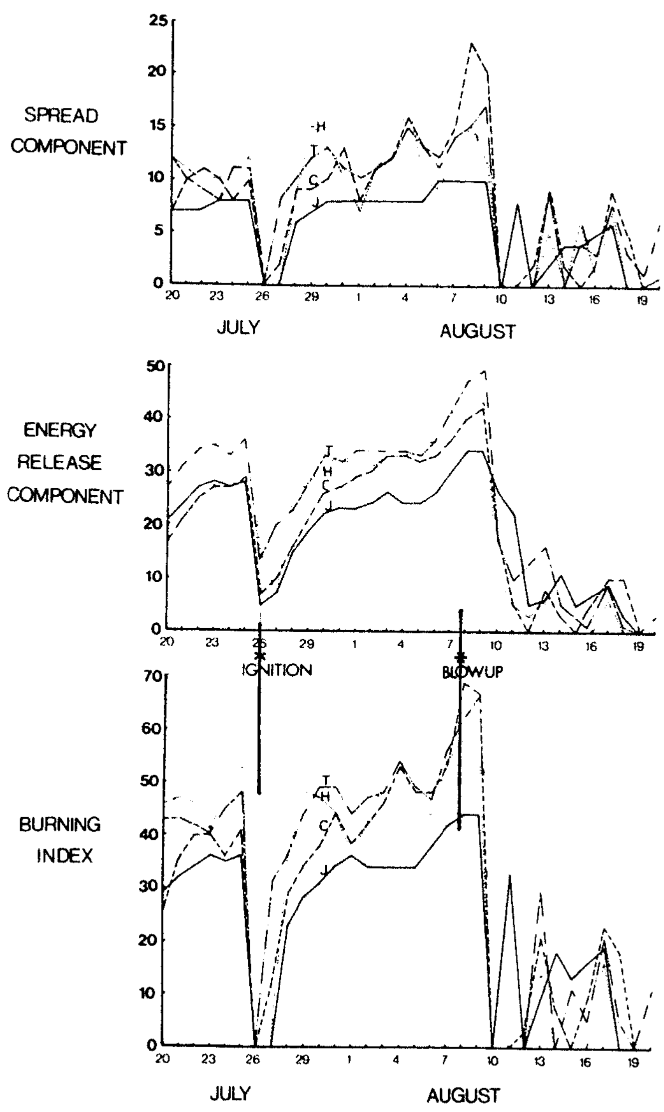

Figure 4. Spread Component, Energy Release Component, and Burning Index from NFDRS before, during, and after the Hoh Fire.

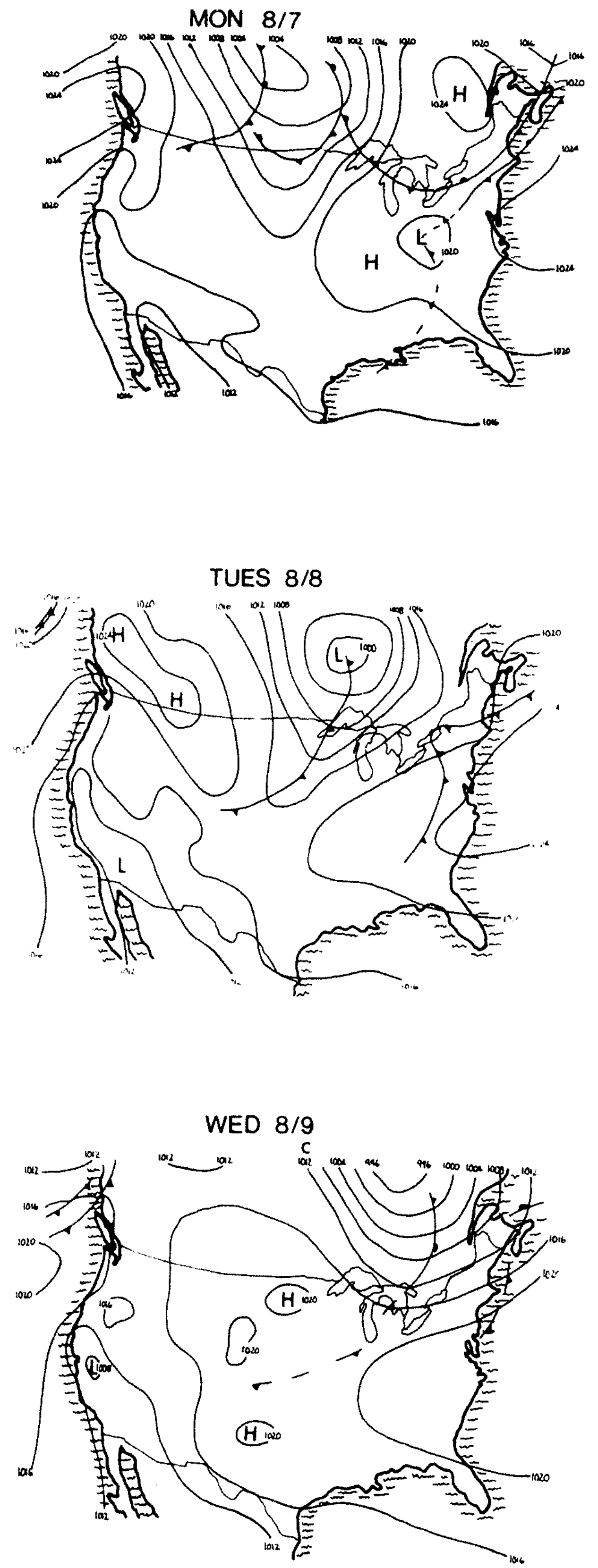

Figure 5. Daily surface weather maps, 0700, showing development of Pacific High pattern of critical fire weather (USDC, NOAA, 1978).

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LITERATURE CITED

Brubaker, L.B. 1980. Spatial patterns of tree growth anomalies in the Pacific Northwest. Ecology (in press).

Deeming, J.E., R.E. Burgan, and J.D. Cohen. 1977. The National Fire Danger Rating System - 1978. USDA For. Serv. Gen. Tech. Rpt. INT-39. Intmtn. For. and Range Exp. Sta., Ogden, Utah. 66 p.

Fritts, H.C. 1976. Tree-rings and climate. Academic Press, London. 567 p.

La Sala, H.J. 1978. Hoh Fire, Olympic National Park: narrative report. USDI National Park Serv. Mimeo, 9 p.

Pickford, S.G., G.R. Fahnestock, and R. Ottmar. 1977. Fuels, weather, and lightning fires in Olympic National Park. USDI National Park Serv./Univ. Wash., Seattle. 97 p.

Ryan, T.A., B.L. Joiner, and B.F. Ryan. 1976. MINITAB student handbook. Duxbury Press, North Scituate, Mass. 341 p.

Sokal, R.R. and F.J. Rohlf. 1969. Biometry. W.H. Freeman and Co., San Francisco. 776 p.

U.S. Dept. Commerce, NOAA. 1978. Daily weather maps, July 31-August 6 and August 7-13. Govt. Print. Off., Washington, D.C. 8 p. ea.