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CORRELATIONS OF CLIMATE, MASS BALANCES, AND GLACIAL FLUCTUATIONS AT MOUNT RAINIER, WASHINGTON, U.S.A., SINCE 1850

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ABSTRACT

Despite the complex interrelationships between climate, mass balance, and glacier response, simplified mass-balance calculations can be correlated with observed glacial behavior. A monthly temperature and precipitation record, extending back to 1850, has been reconstructed for Longmire, Washington, on the southwest flank of Mount Rainier. Calculated mass-balance variations agree with observed glacier behavior since 1850 and with five sets of moraines constructed between 1850 and 1930 at Mount Rainier. Following periods of positive mass balances, trends toward more negative mass balances precede glacial recession with lag times of 1 to 5 yr. Analyses of the reconstructed temperature record and former ice frontal positions suggest that much of a 1°C temperature rise since the latest Neoglacial advances occurred prior to 1850. Correlations of the Mount Rainier mass-balance record with similar ones from Norway and Antarctica indicate generally synchronous climatic trends in the Northern Hemisphere and opposing short-term trends in the Southern Hemisphere since 1850.

INTRODUCTION

Paleoclimatic inferences drawn from geomorphologic data should be based on an understanding of the relationships between climate and glacier fluctuations. Complex interactions exist between prevailing climatic conditions, energy exchange at the glacier surface, mass-balance perturbations, and glacial dynamics (Meier, 1965). Glacier fluctuations represent integrated responses to these factors. Comparisons of mass-balance and climatic data with well-dated terminal variations can place constraints on the timing and magnitude of glacial response to specific climatic changes. This study utilizes a recently dated moraine sequence at Mount Rainier, Washington (Burbank, 1981), and climatic records for the past 130 yr in order to evaluate the relationships between them. Lichenometric studies of moraines constructed by Carbon, Cowlitz, North Mowich, and Winthrop glaciers at Mount Rainier (Figure 1) indicate that episodes of glacier recession commenced around 1768-1777, 1823-1830, 1857-1863, 1880-1885, 1902-1903, 1912-1915, and 1924 (Table 1). In this study, the regional climatic record and calculated mass-balance variations are compared with the recessional moraine chronology in order to determine the timing and nature of the response of the glacier termini to climatic variability.

PREVIOUS INVESTIGATIONS

Efforts to describe short-term mass-balance variations have shown them to be dependent on accumulation due to precipitation, avalanches, and wind-drift,

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and on ablation due to surface energy exchanges. These surface energy exchanges are a complex function of radiative and convective processes that can be modelled using variables such as ambient temperature, wind speed, percent cloud cover, humidity, and short-wave radiation (Föhn, 1973). Unfortunately, climatic records extending back more than 60 yr rarely contain detailed

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measurements of these factors. Consequently, models describing variations in mass balances and the response of glacial termini in the past are usually based upon more readily available temperature and precipitation data. Hence, these models are highly simplified approximations.

Most models based on long-duration climatic data are divisible into two groups: (1) those that consider summer ablation-season conditions to have the most influence on mass balances and terminal fluctuations and (2) those that include the effects of accumulation-season or annual precipitation in their models. Posamentier (1977) developed two models for terminal fluctuations in the Alps: one based on the accumulated effects of the mean summer temperature of a given year and the previous seven summers, and another that utilizes both summer temperature and precipitation. These models explain about 70% of the observed terminal variations since 1900. Hoinkes (1968) showed a correspondence between deviations from the mean of both summer precipitation and temperature with the percentage of advancing Alpine glaciers.

Deviations from the means of annual precipitation and May-August temperatures were correlated through multiple regressions with 16 yr of measured mass balances in the Alps by Martin (1974). Between 73 and 90% of the mass-balance variations could be explained using these two climatic factors. Using winter accumulation and mean summer temperature as a basis for calculating mass balances, Krenke and Popova (1974) demonstrated a short response-time of glacier termini in the Kazbek Mountains to mass-balance perturbations. For South Cascade Glacier, Washington, Tangborn (1968,

In order to discern relationships between glacial and climatic fluctuations, it is desirable to consider as long a climatic record as possible. Although continuous records at Longmire, Washington (842 m) on the southwest flank of Mount Rainier exist only since 1914, the record was extended back to 1850 through correlation with other western Washington stations having longer records. By using this extended climatic record, the relationship between specific climatic trends and the timing of glacier recession can be examined. Simple calculations of mass balances based on this record can be analyzed for their degree of correlation with observed glacier fluctuations. An analysis can then be made of the magnitude and duration of climatic change required to produce the documented glacier fluctuations. No single, meteorological station in Washington has a continuous record since 1850. However, by combining the records from five stations (Figure 1 and Table 2), it was possible to synthesize a nearly unbroken record. Linear regressions of monthly temperature and precipitation based on the overlapping 1914 to 1978 records were run between each station and Longmire.

 TABLE 1

 Lichenometric dates of moraine stabilization

Glacier		Dates ^a						
Carbon	1924	1914	1902	1880	1863	1824	1777	
Cowlitz		1914	1903	1882		1830	1777	
North Mowich		1915	1902	1881	1860	1826		
Winthrop		1912		1885	1857	1823	1768	

^aData from Burbank (1981).

 TABLE 2

 Source, range, and means of correlations forming the basis of the reconstructed Longmire record

		Monthly Correlations (r^2)					
			ation	Temperature			
Station ^a	Period ^b	Range	Mean	Range	Mean		
Vancouver	1852-1867	0.43-0.52	0.47	0.51-0.70	0.61		
Olga	1867-1874	0.27-0.74	0.53	0.19-0.51	0.37		
North Head	1874-1884	0.40-0.68	0.54				
Pt. Townsend	1874-1884			0.30-0.64	0.52		
Tacoma	1884-1914	0.42-0.74	0.61	0.62-0.75	0.70		

^aLocations shown in Figure 1.

^bThe reconstructed record is based on data from these years.

1980) has developed a model based on winter precipitation, mean summer temperature, and summer cloud cover. His results show good agreement with measured mass balances during the past 20 yr.

METHODS OF INVESTIGATION

The correlations were generally strong (Table 2) and had significance levels of greater than 0.99. The regression equations were used to extend the Longmire record to include the period 1850 to 1914. The reconstructed record is most reliable between 1884 and 1914. Olga, Washington, vielded weaker temperature correlations and, as a result, the reconstructed temperature record is least reliable from 1867 to 1874. To test the validity of the interstation correlations and, implicitly, of the reconstructed record, regressions were run on the monthly data from the even-numbered years between 1914 and 1978. Based on these equations, predicted monthly values for the odd-numbered years were compared with the observed values (Figure 2). These indicate that the synthesized record from 1850 to 1914 should reliably record the climatic trends during this period.

Five months of either temperature or precipitation data are missing during the 1870s. In order to generate a continuous record, the mean monthly value (1852-1978) was substituted for the missing data.

The glacier balance year was divided into an accumulation season (October-April) and an ablation season



FIGURE 1. Locations of lichenometrically dated moraines, Mount Rainier, Washington (rectangular boxes). The meteorological stations of Longmire and Paradise are located on the south flank of Mount Rainier. The inset shows the location of the other weather stations that were utilized in this study (N = North Head; O = Olga; P = Port Townsend; T = Tacoma; and V = Vancouver).

(May-September) (Wallén, 1948; LaChapelle, 1965; Tangborn, 1980). Precipitation totals and temperature averages were computed annually and as 3- and 5-yr running means. Whereas the yearly data are noisy, the 5-yr means show persistence of trends (Figure 3) and can be related to observed glacier fluctuations.

Although the relationships between climate, mass balance, and glacier response are not understood in detail (Meier, 1965), estimated mass balances can be computed using climatic data. The strong relationship between ablation and summer temperature (Liestøl, 1967; Tangborn, 1980) allows estimation of mass losses at the steady-state equilibrium-line altitude (ELA). The ELA at Mount Rainier for the maximum Neoglacial advances is estimated to be about 1965 m (Burbank, 1981). The mean summer temperature at the lowest Neoglacial ELA is estimated by lowering the ablation-season temperature at Longmire in accordance with a mean summer lapse rate of 6.2° C 1000 m⁻¹ (Porter, 1977).

Using data from Liestøl (1967) in conjunction with known ablation rates on Blue Glacier (LaChapelle, 1959) and South Cascade Glacier (Meier et al., 1971), mass loss due to ablation was expressed as a function of average temperature at the ELA (Figure 4) during the May-September period (equation 1).

$$A(s) = 80 + 40 \times T$$
 (1)

- A(s) = centimeters of ablation at the average lowest Neoglacial ELA (1965 m), and
 - T = mean ablation-season temperature at the ELA.

In general, weather stations in the foothills are better predictors of precipitation totals for a drainage basin

than are higher-altitude stations where the effects of high winds and copious snowfall render accurate measurements difficult (Rasmussen and Tangborn, 1976). However, on Mount Rainier there is a strong correlation $(r^2 = 0.81)$ between precipitation at Longmire (840 m) and at Paradise (1646 m) (Figure 1), where precipitation is about 25% greater.

Accumulation-season precipitation at the ELA is estimated by three methods. The first (equation 2) relates the ratios of the differences in altitudes between Longmire, Paradise, and the average ELA of the maximum Neoglacial advances to an arithmetic factor that predicts the precipitation at the ELA based on that at Paradise and Longmire.

$$(D1/D2) \times (P1/P2) = [C(w)/P2] = 1.63$$
 (2)

C(w) = centimeters of accumulation at the ELA,

- D1 = the average ELA of the maximum Neoglacial advances-the altitude of Longmire,
- D2 = the altitude of Paradise the altitude of Longmire,
- P1 = accumulation-season precipitation at Paradise, and
- P2 = accumulation-season precipitation at Longmire.

The second method (equation 3) determines the arithmetic factor by using the differences in the index elevation (IE) (Schermerhorn, 1967) between (1) the maximum Neoglacial ELA and Longmire and (2) Paradise and Longmire. The IE is an elevation calculated as a weighted mean of the highest elevations along four 15-km transects measured in the geographic quadrant containing the highest elevations near the station of interest. It correlates much more highly with the annual precipitation at a station than does the actual elevation (Schermerhorn, 1967; Rasmussen and Tangborn, 1976).

$$(D11/D12) \times (P1/P2) = [C(w)/P2] = 1.77$$
 (3)

D11 = the IE at the maximum Neoglacial ELA – the IE at Longmire, and

D12 = the IE at Paradise – the IE at Longmire.

The third method (equation 4) utilizes the difference in the IE between the ELA and Paradise (D11-D12), in conjunction with a precipitation gradient of 235 cm 1000 m⁻¹ of IE gain (Rasmussen and Tangborn, 1976) to determine the factor relating precipitation at Longmire to that at the average ELA of the maximum Neoglacial advances.

$$[P1 + (D11 - D12) \times (235 \text{ cm } 1000 \text{ m}^{-1})]/P2 = [C(w)/P2] = 1.61$$
(4)

In all cases, it is assumed that there is a basically linear change in precipitation as a function of altitude between Longmire and Paradise, and that this trend can



FIGURE 2. Regression equations based on correlations between Tacoma and Longmire of precipitation data from even-numbered years (1914 to 1978) were used to predict the precipitation at Longmire for the odd-numbered years. These examples indicate that the predicted values (dashed lines) closely approximate the observed values (solid lines). Comparisons of predicted and observed values from other stations used in the climatic reconstruction are similar to those shown here. This suggests that the reliability of the reconstructed record should be high.



FIGURE 3. The 5-yr, unweighted, running means of ablation-season temperature and accumulationseason precipitation at Longmire, Washington, show short-term trends of 5 to 10 yr that can be correlated with observed glacier fluctuations. Combined trends toward higher summer temperatures and lower winter precipitation typically precede glacial recession by a few years. The portion of the record where some data are missing is shown by a dashed line. In this figure, and in Figures 5 and 6, the mean 1850 to 1979 monthly value for precipitation or temperature was substituted for the 5 mon that lacked data.

be extrapolated to the ELA. In each case, the value of the arithmetic factor is approximately 1.7 ± 0.1 (equation 5).

$$C(w) = 1.7 \times P2 \tag{5}$$

The net mass balance is defined as the difference between the mass gained during the accumulation season and mass lost during the ablation season (equation 6).

NET MASS BALANCE =
$$B(a) = (1.7 \times P2)$$

- $(40 \times T) - 80$ (6)

Although admittedly a simplification, this estimate of the net mass balance can be directly related to observed glacier fluctuations.

RESULTS

The synthesized (1850 to 1914) and measured (1914 to 1978) records of monthly total precipitation and mean temperature have been used to determine seasonal values for each. For this study, precipitation during the accumulation season and ablation-season temperature are regarded as having the most influence on glacier mass balance, and consequently, on the response of glaciers to fluctuations of climate.

Comparison of the lichenometric dates for moraine stabilization between 1850 and 1930 (Table 1) with the 5-yr means of precipitation and temperature (Figure 3) reveals that climatic trends toward higher summer temperature and decreased winter precipitation are associated with glacier recession. In order to examine the relationship between climate and glacier response more closely, calculations of net mass balances (based on equations 1 to 6) at an assumed maximum Neoglacial ELA of 1965 m have been made (Figure 5). There are a number of potential sources of error in these calculations. These include (1) the reliability of the precipitation totals and temperature means that are based on interstation correlations (Table 2); (2) the simplification of formulas used to define ablation and accumulation at the ELA; (3) the exclusion of other factors that influence mass balance, such as cloud cover (Tangborn, 1980) and "grosswetterlagen" (Hoinkes, 1968); (4) the absence of any direct measurements of climate at the ELA on any of the glaciers with which correlations could be made; (5) the length of the accumulation season, which varies as a function of the altitude of the freezing isotherm (LaChapelle, 1965); and (6) the statistical significance of a relatively small net mass balance, which is calculated as the difference between two large, estimated numbers.

Despite these assumptions and limitations, it is maintained that, whereas specific values for any given year are only approximations, the overall trends defined by the resulting mass-balance curves are valid. Varying the



FIGURE 4. Ablation at the equilibrium-line altitude is predicted as a function of the mean summer temperature. The data shown here are from Storbreen Glacier in south-central Norway (Liestøl, 1967), South Cascade Glacier in the North Cascade Range (Meier et al., 1971), and Blue Glacier in the Olympic Mountains of Washington (LaChapelle, 1959).



FIGURE 5. Calculations of annual amounts of accumulation, ablation, and net mass balance were made at the equilibriumline altitude (1965 m) determined for the maximum late Neoglacial advances. High year-to-year variability renders comparisons with observed glacial fluctuations difficult.



FIGURE 6. Comparison of the 3-yr running mean of net mass balance at the Neoglacial ELA of 1965 m with the dates for moraine stabilization as determined by lichenometric dating suggests a direct correlation. The documented glacial recessions at Mount Rainier commence 1 to 5 yr after the net mass balance begins to decline from positive values sustained for several years.



FIGURE 7. Calculations of the net mass balance at the present ELA of 2125 m are in agreement with observed trends since the 1920s.

parameters used in the mass-balance calculation (equation 6) by 10 to 20% changes the annual values, but not the basic shape of the curve (compare Figures 5 and 7). Similar calculations of mass balances for South Cascade Glacier (Tangborn, 1980) and Storbreen Glacier (Liestøl, 1967) have been shown to describe measured fluctuations quite accurately. Tangborn's equations are based on multiple regressions of measured mass balances with winter precipitation, mean summer temperature, and summer cloud cover, whereas Liestøl utilized summer degree-days and winter precipitation to calculate mass balances. Both of these studies rely on longduration meteorological data from low-altitude stations, well removed from the glaciers being studied.

A comparison of the 3-yr running mean of the calculated net mass balance at Mount Rainier with the dates for moraine stabilization (Figure 6) reveals a correlation between decreasing net mass balance and periods of moraine stabilization. Further confirmation of this correlation is provided by evidence from Nisqually Glacier for still-stands around 1875 and 1900, as well as for glacier thickening and growth for several years after 1932 and 1945 (Brockman, 1938; Harrison, 1956; Post, 1963; Veatch, 1969). These observations agree with the calculated positive net mass balance during each of these periods (Figures 6 and 7).

It is noteworthy that no dated moraines correspond with the trend toward a negative balance between 1865 to 1870. There are several possible explanations for this apparent anomaly: (1) this study may have encompassed an insufficient number of glaciers to show all recent fluctuations; (2) moraine segments from this period may be too short (<200 m) to be dated accurately with lichenometry; (3) moraines built during this time may have been overrun by the subsequent advance in the late 1870s; or (4) the duration of the period of positive mass balance may have been insufficient to trigger an advance. The sharp rise from 1865 to 1867 to a positive mass balance results primarily from a 2-yr period (1867 to 1868) during which precipitation was 30% above normal.

At present the average steady-state ELA (2125 m) lies about 160 m above the ELA determined for the maximum Neoglacial advances (Meier, 1963; Burbank, 1981). If a summer lapse rate of 6.2° C 1000 m⁻¹ (Porter, 1977) is applied, the mean ablation-season temperature at the present ELA would be about 1°C lower due to this altitude difference, assuming the ELA depression was due to temperature alone. Based on the relationship between temperature and ablation (Figure 4), this temperature decrease would reduce the amount of ablation by an annual average of 40 cm. Average winter precipitation would be expected to increase 10 to 20 cm in comparison to that at the maximum Neoglacial ELA, assuming an altitude-dependent relationship similar to that used in equations 2 to 5. Calculations of the net mass balance at the present ELA display good agreement with recent trends in glacier activity (Figure 7). Whereas the major retreat and thinning from 1920 to 1945 (Veatch, 1969) correlates with the dominantly negative mass balances calculated for this period, the widespread glacier rejuvenation and thickening observed since 1945 (Hubley, 1956; Post, 1963) is associated with balanced or positive regimes from 1945 to 1975. A striking, but short-lived, episode of thickening of Nisqually Glacier in the early 1930s (Veatch, 1969) supports the strongly positive mass balances calculated for this period.

DISCUSSION

The interpretation of the relationship between the reconstructed mass-balance record and the timing of glacial recession since 1850 rests, in part, on the accuracy of the dates for moraine stabilization. The precision of the late 19th-century moraine dates is about ± 3 yr, whereas the 20th-century dates have a precision of ± 2 yr (Burbank, 1981; Porter, 1981a). The measured range in the timing of moraine stabilization on Mount Rainier ranges from 2 to 6 yr (Table 1). The synchronous behavior may reflect the comparable size and perhaps similar activity indices of the glaciers studied.

The tightly grouped dates for moraine stabilization and inferred glacial recession permit ready comparison with the mass-balance record. Glacier recession commenced shortly after the 3-yr running mean of net mass balance began to decrease (Figure 6). The lag time between the climatic change and the glacial response appears to be 1 to 5 yr. This indicates that, if a glacier has achieved a balanced regime during a readvance or halt, the response time in the ablation zone may be both rapid to the climatic change and synchronous among different glaciers. Mass-balance considerations suggest that moraines should have been formed in the early 1920s following a build-up of ice in the previous 4 to 6 yr. However, the rapidity of climatic amelioration led to stagnation, followed by gradual thinning and recession, of the lower regions of most of the glaciers that were inspected. On Carbon Glacier, the only major glacier without extensive stagnant ice in the proglacial area, lateral moraines dating to 1924 are found (Burbank, 1981).

A number of considerations have led some investigators to conclude that temperature is the primary factor controlling recent glacier behavior. The observed rise in the mean annual temperature of about 1°C since 1890 in many areas of the Northern Hemisphere (LaChapelle, 1965; Hoinkes, 1968; Brinkmann, 1976; Karlén and Denton, 1976) correlates well with both the extensive glacier retreats throughout the world (Porter and Denton, 1967) and with the apparent rise in equilibriumline altitudes of between 100 and 200 m that have been observed in Scandinavia (Karlén and Denton, 1976; Matthews, 1977), New Zealand (Porter, 1975), and on Mount Rainier (Meier, 1963; Burbank, 1981). Tempera-

ture changes of this magnitude may be sufficient to explain changes in the Neoglacial extent of glaciers (LaChapelle, 1965; Tangborn, 1980).

However, at Mount Rainier, it does not appear that the post-1890 temperature rise is primarily responsible for the recessional behavior that has dominated glacial fluctuations since the latest Neoglacial advances. Although a rise of 1.2° C in the decadal mean ablationseason temperature occurred between 1890 and 1950 at Longmire, the average summer temperature during this period of general glacier recession is 0.15° C below the 1850 to 1978 mean, and is about 0.6° C below the 1850 to 1890 mean. These data suggest that, disregarding precipitation, mass loss should have been greater between 1850 and 1890 than between 1890 and 1950.

There has been a 7% decrease in accumulation-season precipitation at Longmire from an average of 182 cm during the period 1850 to 1910 to 170 cm between 1910 and 1978. Nevertheless, the higher precipitation during the second half of the 19th century is insufficient to account for the depression of the ELA during the maximum Neoglacial advances to 160 m below its present position. Based on data from the west flank of the Cascades (Porter, 1977), precipitation increases of this magnitude would have to be coupled with an ablation-season temperature decrease of between 0.8 and 0.9°C in order to achieve an ELA that was 160 m lower than at present (Table 3). Moreover, the higher precipitation between 1850 and 1910 can be attributed primarily to the period 1892 to 1909, during which time precipitation was 15 to 20% above average, rather than to persistently higher precipitation between 1850 and 1910. Furthermore, the increased precipitation at the end of the last century apparently caused stillstands, but definitely did not trigger major advances to the earlier maximum Neoglacial limits, despite the much-cooler-than-average temperatures during the ablation season.

The dominantly negative net mass balances calculated between 1850 and 1890 (Figure 6) suggest that substantial thinning of the glaciers probably occurred during this period, although the actual retreat of the termini was not large. Due to this thinning, the glaciers would have been sensitive to future climatic perturbations. Consequently, the rise in ablation-season temperature after 1910 coupled with the decreased precipitation would have caused the observed rapid retreat of the termini between 1910 and 1940 (Figure 8). At Mount Rainier, this sequence of responses explains the moraine distribution and recessional behavior of those glaciers that have receded over 2 km since the early 19th century and that lack extensive supraglacial debris (e.g., Cowlitz and North Mowich glaciers).

The rise in the ELA of 160 m since the maximum Neoglacial advances requires a combination of changes in the long-term means of temperature and precipitation. If it is assumed that precipitation did not decrease by more than 20% since 1850, the mean temperature would have to rise about 1°C to effect this change (Table 3). However, the temperature data from Long-

 TABLE 3

 Relationship of climatic change to lowering of the ELA

Precipitation increase	Summer Temperature Change (°C) Amount of ELA Lowering			
(%) ^a	900 m ^a	160 m		
0	-5.6	-0.92		
7	-5.2	-0.88		
20	-4.6	-0.77		

^aData from Porter (1977).

mire reinforces that from California, Oregon, and Washington that indicate no long-term rise in the mean annual temperature since about 1850 (Roden, 1966). The lichenometrically dated moraine chronology suggests that this temperature rise did not occur after 1890, but rather sometime between 1770 and 1830, at which time the glaciers were at or near their maximum Neoglacial extent (Burbank, 1981). Climatic reconstructions from the mid-continent also indicate temperature minimums around 1750 and a rapid rise of about 0.5°C in the mean summer temperature between 1750 and 1860 (Bernabo, 1981). The temperature rise at Mount Rainier initiated and sustained the major recession of all the glaciers during the last 150 yr. Superimposed on this longterm trend are the short-term fluctuations in accumulation-season precipitation and ablation-season temperature that have modulated the chronology of glacial stillstands and readvances since 1850.

Although ELAs have risen about 150 m in both the Northern and Southern hemispheres since the Neoglacial maximum advances of the past several hundred years, moraine chronologies suggest that the timing of short-lived readvances that punctuate this recessional period was not synchronous between hemispheres (Porter, 1981b). The development of long mass-balance records permits comparisons of continuous time-series data between hemispheres. Linear regressions were run among the records from Mount Rainier, Storbreen Glacier in central Norway (Liestøl, 1967), and glaciers on Deception Island near the Antarctic Peninsula (Orheim, 1972) (Table 4). Although weak or insignificant correlations are found between pairs of annual mass-balance data, comparisons of both 5- and 10-yr, unweighted, running means greatly strengthen the correlations between Mount Rainier and sites in both hemispheres. Despite distinct differences in the timing of moraine stabilization since 1850 in Scandinavia and North America (Burbank, 1981), the positive correlation (r =0.43) of the 10-yr running means between Mount Rainier and Storbreen Glacier indicates that climatic variability has been fairly synchronous during the past 130 yr at these Northern Hemisphere sites. The greatest discrepancies in the mass-balance records occur between 1895 and 1902 and in the 1920s. Whereas the Mount



FIGURE 8. Although the most dramatic retreat of glacial termini occurred between 1910 and 1940, the climatic data indicate that substantial thinning probably occurred between 1820 and 1910. Figure 8A depicts a hypothetical cross-section of a low-gradient, valley glacier that experiences equal thinning over equal lengths of time. The uneven pattern of recession of the active terminus is similar to that observed at Cowlitz Glacier (8B) and North Mowich Glacier (8C), both of which occupy low-gradient valleys and have stagnant ice in their proglacial zones.

Rainier record shows strongly positive annual balances during the former period and negative ones during the latter period, the Storbreen record exhibits opposing trends (Figure 9). Much of the difference in the moraine chronologies since 1850 between these two areas is explained by the contrasting mass-balance records during these periods.

Strong anticorrelations exist both between Mount Rainier and Deception Island (r = -0.54) and between

Storbreen Glacier and Deception Island (r = -0.58). Hence, despite the comparable amount of rise in the ELA in most areas, these data support the concept of the nonsynchrony of late Neoglacial climatic events in the Northern and Southern hemispheres (Orheim, 1972, 1977). These differences are also reflected in the contrasting Neoglacial moraine chronologies from both hemispheres (Porter, 1981b).

	Annual		5-year running means		10-year running means	
	Storbreen Gl.	Deception Is.	Storbreen Gl.	Deception Is.	Storbreen Gl.	Deception Is.
Mount Rainier	-0.01ª	-0.17	0.22	-0.42	0.43	-0.54
	101 ^b	119	97	115	92	110
	(.92) ^c	(.06)	(.03)	(.000)	(.000)	(.000)
Storbreen Gl.	· · ·	0.004		-0.36	, ,	-0.58
		101		97		92
		(.97)		(.000)		(.000)

 TABLE 4

 Correlations of mass-balance records (annual 5- and 10-year running means)

^aCorrelation coefficient.

^bNumber of data pairs on which regression is based.

^cProbability of the correlation being fortuitous (0.99 = highly fortuitous).



FIGURE 9. Comparison of the cumulative mass-balance records from Mount Rainier and Storbreen Glacier indicates similar tendencies toward overall recession during the past 130 yr. The discrepancies in the moraine chronologies between these areas (Burbank, 1981) reflect the contrasting mass-balance trends between 1895 and 1925.

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CONCLUSIONS

Mass-balance calculations, based on a reconstructed climatic record since 1850, correlate well with dated moraines and historical observations of glacial fluctuations at Mount Rainier. Glacial recession usually commences 1 to 5 yr after a change toward negative mass balance. Long-term changes in late Neoglacial extent are explained by a 1°C temperature rise that began between 1770 and 1830. Since then, glacier behavior has been modulated by short-term variations in both temperature and precipitation.

Comparisons of mass-balance records from different areas depict generally synchronous climatic trends in the Northern Hemisphere. Strong negative correlations between the Northern and Southern hemisphere records indicate nonsynchronous, short-term behavior and are in agreement with established late Neoglacial moraine chronologies.

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