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SPATIAL PATTERNS OF MASS-BALANCE FLUCTUATIONS OF NORTH AMERICAN GLACIERS

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ABSTRACT. Long-term records (10–30 years of measurements) of North American glaciers are compared using Lliboutry's simplified linear model. This model separates the mass balance into two additive terms, one dependent on the location of the glacier and the other on time. The time-dependent term provides a common signal for the variations of different glaciers. Principal-component analysis indicates that these similarities amount to between 65 and 70% of the total variance for glaciers up to about 500 km apart. Within this distance, similar variations of mass balance and, therefore the same yearly climatic variations, can be observed.

INTRODUCTION

Glacier fluctuations are good indicators of climatic change. The most obvious glacier change is the movement of the terminus. However, this response also depends sensitively on glacier shape and dynamics, as is evident from the occurrence of advancing and retreating glaciers in close proximity to one another. A reliable indicator of climatically induced variations must therefore take into account the total change in glacier volume rather than just changes in snout position. The mass balance (yearly increase or decrease of ice) satisfies this requirement.

However, since mass-balance measurements are time- and labor-intensive, they are generally restricted to a few selected glaciers, raising the question of how large an area do they represent.

It has already been shown that simple mass-balance variation patterns exist (Reynaud, 1980; Reynaud and others, 1984); although variations do not appear synchronized between different mountain ranges for the short period of available measurements, mass-balance variations are statistically similar over large mountainous regions like the Alps or Scandinavia. This homogeneity of mass-balance variation makes it possible to monitor the climatic variations of a whole mountain range. From a glaciological point of view, the homogeneity is also of interest since it means that the mass-balance fluctuation history of a whole area is applicable to any glacier in that area. To check whether this homogeneity is a general rule, applicable even under very different physiographic settings and weather patterns, North American mass-balance measurements are analysed below.

DATA

The mass-balance measurements for the various glaciers were made by different organizations and the series starts or ends in different years (Table I). Only glaciers with mass-balance series long enough to show a sequence of fluctuations of at least 10 years were considered in this study. There are 11 such glaciers in the mid-latitudes and four in the high latitudes (Fig. 1). The longest sequences are those of South Cascade Glacier and Blue Glacier (Washington, U.S.A.), which have been measured every year since 1956. The next longest records, going back to 1965 are for three Canadian glaciers: Peyto Glacier, in the Rockies, and Place and Sentinel Glaciers in the Coast Mountains. The others cover only 10 years or less. The mid-latitude glaciers are especially interesting because they cover an area similar to the Alps in size.

The cumulative mass balances of all these glaciers have been plotted in Figure 2, showing ice volumes with diminishing or increasing trends. The most striking feature is the absence of a common trend. Some curves increase (Blue and Sentinel Glaciers), while others decrease (Peyto, Place, and South Cascade Glaciers). This lack of synchronism between glaciers has long been recognized. However, there are some similarities, including the pronounced bump for Sentinel, Peyto, Place, and South Cascade Glaciers around 1976. This observation suggests that a finer comparison could yield further similarities.

METHOD

The basic idea is that, although the mass balances at different sites may vary for a given year, their variations with time are similar for all locations. An extensive statistical study was conducted using point measurements from Saint Sorlin Glacier, France (Lliboutry, 1974), and a simplified model was used for various glaciers of the Alps (Reynaud, 1980). This model produces a signal that is representative of the group of glaciers:

$$b(j,t) = \alpha(j) + \beta(t) + \varepsilon(j,t)$$

where $b(j,t)$ is the mass balance of glacier j in year t, $\alpha(j)$ is a time-independent term reflecting the physical characteristics of the glacier (elevation, orientation, ...), $\beta(t)$ is time-dependent only, representing the common signal observed for all glaciers of the Alps, $\varepsilon(j,t)$ is the residual, reflecting the closeness between reality and the model.

These values are computed in the following way: $\alpha(j)$ is the mean mass balance of glacier j over the period of study T:

$$\alpha(j) = \frac{1}{\mathrm{T}}\sum_{t=1}^{T} b(j,t).$$

The $\beta(t)$ signal is evaluated by averaging the $b(j,t) - \alpha(j)$ of the M glaciers:

$$\beta(t) = \frac{1}{TM-1}\sum_{t=1}^{T}\left[b(j,t) - \alpha(j)\right]$$

and a table of residuals can be computed:

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$\varepsilon(j,t) = [b(j,t) - \alpha(j)] - \beta(t)$. The standard deviation of the residuals evaluates the dispersion or the uncertainty in the $\beta(t)$ sequence:

$$\sigma_\varepsilon^2 = \frac{1}{TM - 1}\sum_{t=1}^{T}\sum_{j=1}^{M}\varepsilon^2(j,t).$$

A correlation coefficient can be used to compare two series of mass balances and evaluate their similarity. To compare more than two series, a different method such as principal-component analysis is needed. This method gives a simple visual representation of how similar, or different, the series are. When the first two components are plotted against each other, each series appears as a point. The closer two points are, the better is the agreement between the two corresponding series. The percentage of the total variance explained by the first component reflects the degree of similarity between the series in the data set. The other components may help in identifying the causes of the differences in the series.

DATA ANALYSIS

The method used requires a complete, rectangular data matrix. This is not the case here (Table I), since the mass-balance measurements start or end in different years. To use all the variable time series, the data set in Table I was broken into sub-sets covering the same time periods.

The first sub-set, for the period 1966–84, includes five glaciers chosen from the longest series. The deviation from the mean for each glacier, $b(j,t) - \alpha(j)$, has been plotted as a function of time in Figure 3. Contrary to Figure 2, a common signal emerges. For most years, the values for the five glaciers can be found within an interval of 1 m, while variations with time can be as high as 2 m. This is especially noticeable for years including a sudden jump, such as 1970 and 1976. Although for some years the mass balance of a particular glacier may be well outside the average, such as South Cascade Glacier in 1972, a general trend can be distinguished for all the glaciers. The principal-component analysis confirms this result: 74% of the variance of the data set is explained by the first component. The second component, which accounts for 14%, groups glaciers together more or less according to their geographical distribution. It seems to describe how much of the variance of the mass balance can be attributed to location differences. The maritime glaciers like South Cascade Glacier, with higher standard deviations (1.1 m w. eq.) than the continental glaciers such as Peyto Glacier (0.6 m w. eq.), are shown in the lowest values of the second principal component.

The three Canadian glaciers, Peyto, Place, and Sentinel Glaciers, show an interesting phenomenon: Peyto Glacier, in the Canadian Rockies, 500 km from the coast, responds mostly to the variations of summer temperatures and has been decreasing during the period of mass-balance measurements, while Sentinel Glacier, in the Coast Mountains, is influenced by winter precipitation and has been increasing rapidly. Place Glacier, also in the Coast Mountains, but farther inland where the climate is less maritime, responds to a more traditional combination of summer temperature and winter precipitation (Letréguilly, 1988). So, although the three glaciers represent different regimes (Sentinel Glacier has generally a more positive mass balance than Peyto Glacier), they experience the same changes in mass balance from year to year.

TABLE I. NORTH AMERICAN SPECIFIC ANNUAL MASS-BALANCE SERIES USED IN THIS STUDY (m w. eq.)

Year	*R.R.*	*Wo.*	*Blue*	*S.C.*	*Pey.*	*Pla.*	*Sen.*	*Zav.*	*Bri.*	*Syk.*	*Hel.*	*Bab.*	*Whi.*	*Wol.*	*Gul.*
1956			1.4	0.2											
1957			−1.1	−0.2											
1958			−1.7	−3.3											
1959			−0.1	0.7											
1960			0.0	−0.5								−0.9	−0.4		
1961			0.7	−1.1								0.1	0.1		
1962			0.4	0.2								−1.0	−0.8		
1963			−0.3	−1.3								−0.1	−0.1		
1964			0.9	1.2								0.2	0.3		
1965			−0.3	−0.2								0.1	0.0		
1966	0.1	−0.2	0.6	−1.0	0.1	0.1	0.1					0.1	0.0	−0.3	0.1
1967	−1.0	0.1	0.6	−0.6	0.0	−1.2	−0.2					0.2	0.1	−2.0	−0.1
1968	0.4	0.2	0.3	0.0	0.3	−0.1	0.4					−0.5	−0.4	−1.5	−0.5
1969	−0.2	−0.8	0.9	−0.7	−0.4	−0.2	0.1					0.1	0.0	−1.0	−0.8
1970	−1.6	−1.9	−0.1	−1.3	−1.7	−1.5	−1.3					0.1	0.0	1.0	0.4
1971	−0.9	0.1	1.4	0.6	−0.4	−0.3	0.6					−0.5	−0.2	0.8	−0.2
1972	−0.1	0.3	0.6	1.4	−0.2	−0.3	0.3					0.3	0.1	−0.3	−0.1
1973	−0.0		0.1	−1.0	0.4	−0.3	0.8					0.1	0.2	0.9	0.0
1974	−0.1	0.7	2.4	1.0	0.2	0.6	2.1					0.1	−0.1	−1.2	−1.1
1975	−0.6	0.4	1.1	−0.1	−0.6	−0.2	0.9					0.3	0.2	0.4	−0.4
1976			1.7	1.0	0.6	0.8	1.5					0.1	0.1	−0.3	−1.0
1977			−0.9	−1.3	−0.2	−1.2	−1.3	−0.3	−0.8	−0.4	−1.5	−0.5	−0.4	1.9	0.1
1978			0.7	−0.4	−1.0	−0.4	+0.4	−0.3	−0.3	0.1	−0.8		−0.1	0.7	−0.1
1979			−1.9	−2.3	−0.8	−2.2	−1.7	−0.7	−1.4	−1.0	−2.7		−0.1	−1.0	−0.8
1980			−1.1	−1.0	−1.0	−0.9	0.3	−0.7	−0.8	−0.3	−0.9			2.9	−0.1
1981			−1.1	−0.8	−1.1	−1.1	0.2	−0.2	−0.4	0.1					
1982			1.8	0.1	−0.6	−0.7	0.9	−0.5	−0.5	−0.1	−0.3				
1983			0.9	−0.8	−0.4	−0.4	1.2	0.4	0.2	0.6	−0.2				
1984			1.2	0.1	−0.6	−0.3	0.8	0.3	−0.2	0.7	−0.3				
1985			0.6	−1.2											
1986			−0.6												

Blue: Armstrong, 1987. South Cascade (S.C.): Tangborn, 1980; Krimmel, 1987. Peyto: Young, 1981. Ram River (R.R.). Wooley (Wo.). Place (Pla.). Sentinel (Sen.). Zavisha (Zav.). Bridge (Bri.). Sykora (Syk.). Helm (Hel.): Mokievsky-Zubok and others, 1985. Baby (Bab.): Kasser, 1967, 1973; Müller, 1977; Haeberli, 1985. White (Whi.): Alean and Müller, 1977; Haeberli, 1985. Wolverine (Wol.). Gulkana (Gul.): personal communication from L. Mayo.

Fig. 1. Top: location of the 15 North American glaciers used in this study. Bottom: schematic cross-section of the mid-latitude glacier area from the ocean to the interior, showing approximate location. Mean elevation of Peyto Glacier is 2610 m.

The two following data sub-sets include a larger number of glaciers, but the series is shorter: 1966–75 (Fig. 4) and 1976–84 (Fig. 5). Although in some particular years, such as 1982, individual glaciers differ, the two plots also show an overall agreement between the mass-balance series. The principal-component analysis evaluates the overall similarities at 66% and 74%, respectively. Therefore, it appears that temporally shorter but spatially wider data sets also reveal a relatively homogenous (a uniform) mass-balance response.

The next sub-set, involving Blue Glacier and South Cascade Glacier, offers the longest period of comparison (30 years). Plots of their cumulative mass balances (Fig. 6a) show completely different behaviours: South Cascade Glacier decreases while Blue Glacier increases. However, for plots of $b(j,t) - \alpha(j)$, the two glaciers show similar fluctuations. The correlation between these two series shows that there is an agreement: $R = 0.69$. The series being 30 years long, this value is significant at the 95% level of confidence. The cumulative deviation from the mean has also been plotted (Fig. 6d). Like Figure 6a, this graph shows the fluctuation of ice volume of each glacier but with the dominant trend removed. These dominant trends are probably caused by the differences between the two glaciers (elevation, length, orientation, distance to the coast ...), or differences in glacier dynamics, which determine the glacier's memory, while the fluctuations with time reflect the year-to-year changes in the climate characterizing the area in which the two glaciers are located. Without these long-term trends, the two mass-balance curves show the same history of variations.

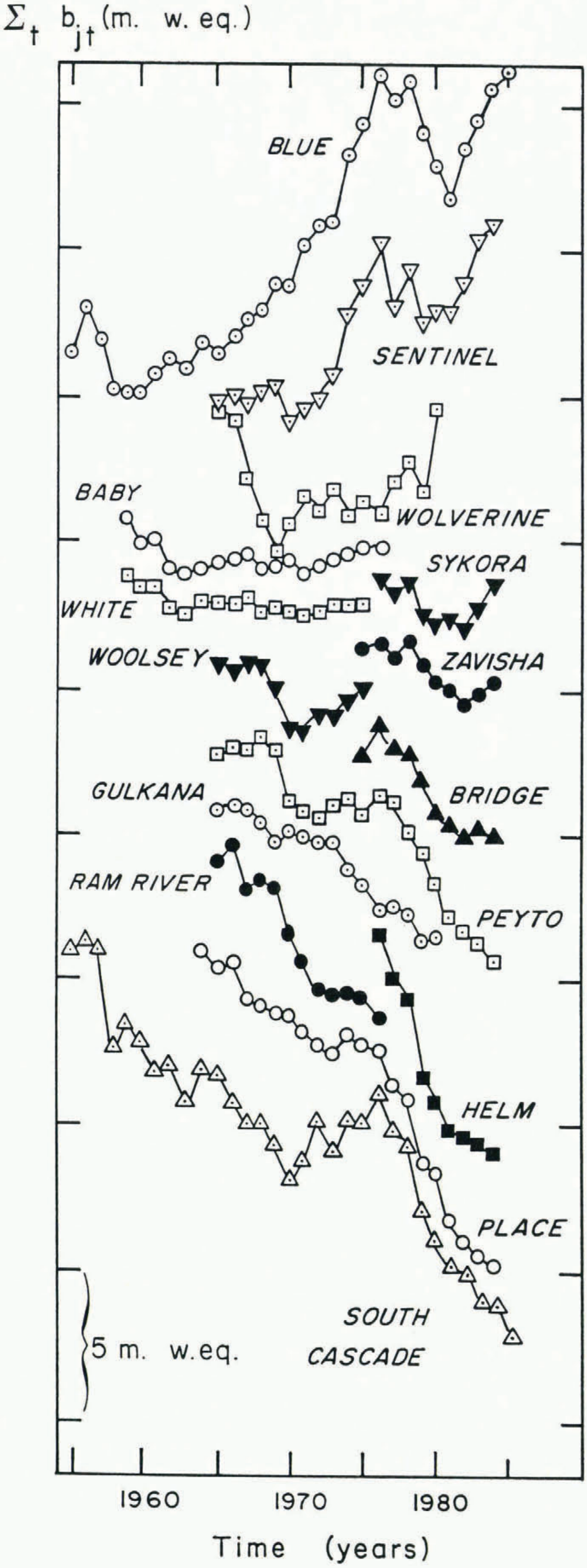

Fig. 2. Cumulative mass balance of the glaciers used in this study (m w. eq.). All series are cumulated starting from zero m w. eq. The origin was then shifted vertically for clarity of the plot. The vertical axis is only there for scale. This graph shows clearly the diversity of glacier response: some glaciers have increased quickly in size, such as Blue Glacier, while others, such as South Cascade Glacier, have decreased.

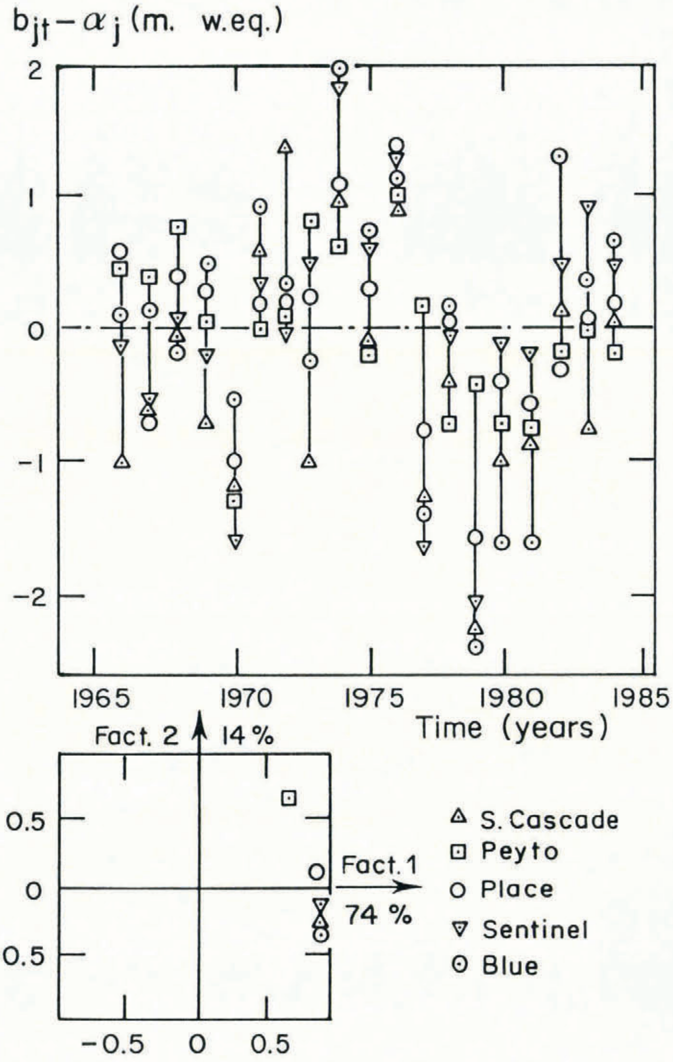

Fig. 3. Variations with time of the centered mass balance (m w. eq.) of five glaciers for the period 1966–84. The standard error σ_b of all the mass-balance series is 0.9 m w. eq. The standard error σ_ε of the residuals ε is 0.5 m w. eq. The smaller plot below shows the first two factors of a principal-component analysis.

Four mass-balance series are also available in the Arctic. The mass balance of the mid-latitude glaciers and those of Gulkana and Wolverine Glaciers in Alaska (Fig. 7), or Baby and White Glaciers in the Canadian Arctic (Fig. 8), show no similarity in variations. However, looking at the plot of $b(j,t)$ with time for Baby and White Glaciers, it can be seen that the two curves are very similar. A cross-correlation between these two series gives a correlation coefficient R of 0.93, indicating that the linear model of variations can also be applied locally there. The two glaciers are very close to each other, only 3 km apart. However, they differ greatly in size, since Baby Glacier is 1.4 km long while White Glacier is 15 km long.

Only a weak relation (R = 0.55) can be found for the two Alaskan glaciers, as already found by Meier and others (1980). It would seem that the two glaciers are too far apart to produce the same variations. This example gives an indication of the area over which the linear model can be successfully applied to derive a common signal for all the glaciers on such a small span of time.

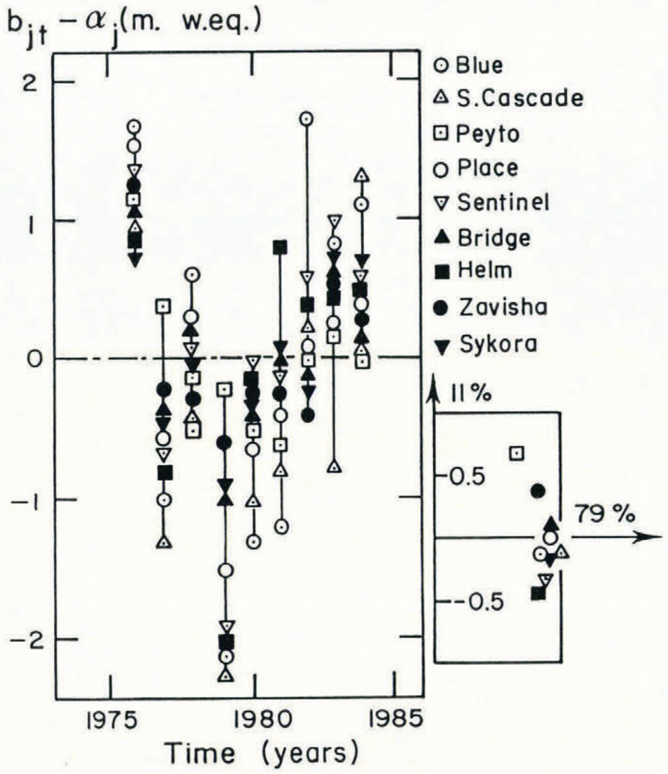

Fig. 4. Variations with time of the centered mass balance (m w. eq.) of seven mid-latitude glaciers for the period 1966–75. The standard error σ_b of all the mass-balance series is 0.7 m w.eq. The standard error σ_ε of the residuals ε is 0.4 m w. eq. The smaller plot on the right is the first two factors of a principal-component analysis.

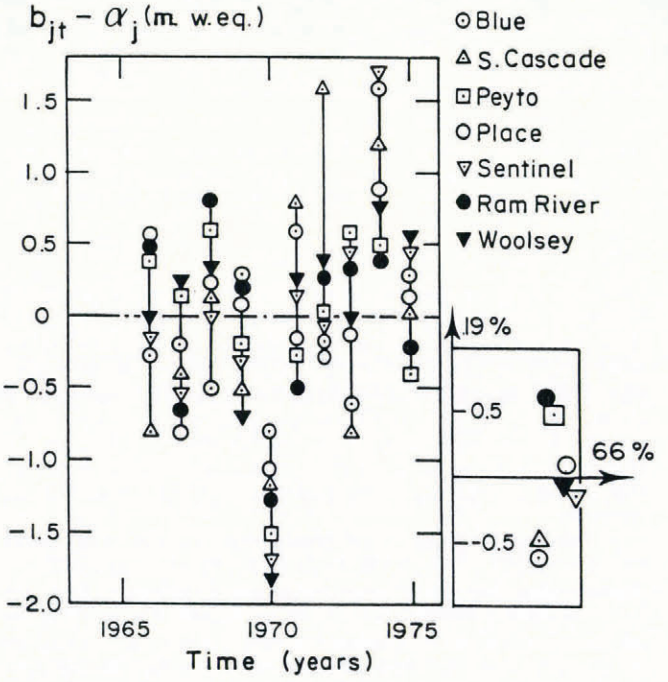

Fig. 5. Variations with time of the centered mass balance (m w. eq.) of nine mid-latitude glaciers for the period 1976–84. The standard error σ_b of all the mass-balance series is 0.8 m w. eq. The standard error σ_ε of the residuals ε is 0.4 m w. eq. The smaller plot on the right is the first two factors of a principal-component analysis.

DISCUSSION

The mass-balance series of different glaciers are comparable over periods of 10–30 years and areas of a few hundred kilometers provided that uncertainty in the mass-balance measurement is taken to be about 30–40% (unexplained variance), which corresponds to measurement errors of 0.20–0.40 m. This is higher than the 0.20 m usually assumed for several possible reasons. For example, parts of many glaciers cannot be reached, such as avalanche areas and crevasse zones. The local mass balance of these areas is then estimated, not measured, possibly introducing an additional error in the computation of the mass balance. This error, if any, is hopefully constant from year to year, which means that the α(j) value of the linear model is not known exactly. However, the yearly fluctuation β(t) should not be influenced.

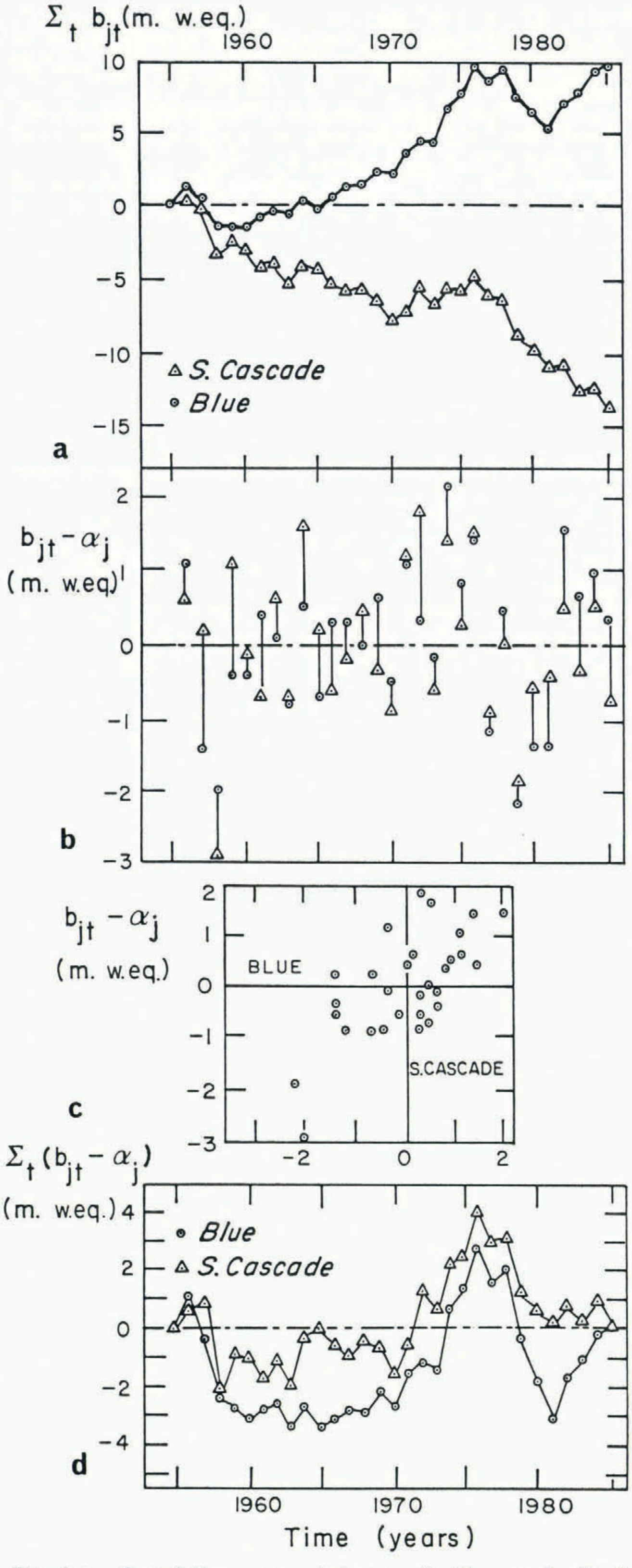

Fig. 6. a. Cumulative mass balance of Blue and South Cascade Glaciers. b. Variation with time of the centered mass balance ($b(j,t) - \alpha(j)$) of Blue–Cascade Glaciers (σ_b = 1.0 m w. eq.; σ_ε = 0.4 m w. eq.). c. Cross-correlation between South Cascade and Blue Glaciers centered mass balance ($b(j,t) - \alpha(j)$). The straight line is the first diagonal. R = 0.69. d. Cumulative centered mass balance $\Sigma(b(j,t) - \alpha(j))$ of Blue and South Cascade Glaciers as a function of time (m water).

Nevertheless, other phenomena can introduce noise into the $\beta(t)$ signal, such as the unevenness of the glacier surface, which is especially significant in the ablation zone. From a similar study in Antarctica, Pettre and others (1980) indicated that, with a normal network of stakes, the mass balance was not known to a precision greater than the average size of the sastrugi. On mountain glaciers, bumps from ablation on the ice can sometimes be as high as half a meter.

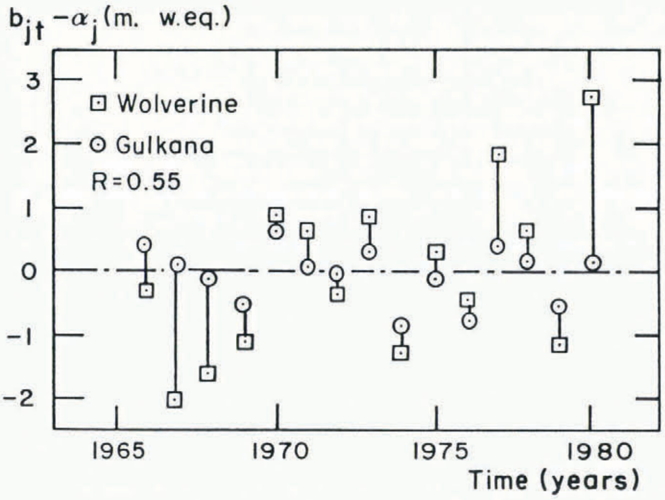

Fig. 7. Variations with time of the centered mass balance (m w. eq.) of two Alaskan glaciers for the period 1966–80.

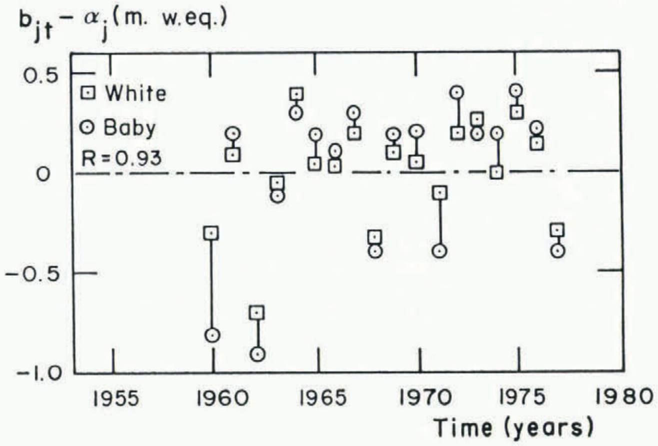

Fig. 8. Variations with time of the centered mass balance (m w. eq.) of two glaciers from Axel Heiberg Island in the Canadian Arctic.

Metallic poles are heat conductors, so, when a large part of such a pole is above the glacier surface, it absorbs the heat from the Sun's rays and melts the ice around the buried part, causing the pole to sink into the ice. On the other hand, when the water freezes in the hole, it tends to push the pole out of the ice. Other sources of error can be mentioned, such as incomplete knowledge of refreezing at depth (internal accumulation), correctly integrating point data to form an areal average, and the absence of time visits to record accurately the beginning or end of a mass-balance interval. Do those phenomena affect the mass-balance values significantly? Such processes are not very well understood and must therefore be considered as possible sources of random error.

CONCLUSION

As for the Alps, a common trend can be found in the mass-balance time series of the mid-latitude glaciers of North America: 60–70% of the variance of these series is identical and a signal characteristic of the area can be computed using Lliboutry's simple model of linear variation. Although different glaciers show very different mass balances for a given year, the variation with time, centered around the mean, is similar for all these glaciers. The variations in the annual mass balance are correlated over distances up to about 500 km.

This relatively good agreement in the variation of the mass balance indicates that any glacier gives a signal that is representative of its surrounding area. Thus, a known temporal variation for a certain glacier can be applied to another glacier located within 500 km. From a more general point of view, the mass balances of mountain glaciers can really be used as an annual climatological indicator.

Of course, the results of this statistical study on such a small data set have to be interpreted with care. These results are indications more than certainties. It will take a few more decades of regular measurements before firm conclusions can be drawn, emphasizing the importance of continuing the measurement programs that have been started on these glaciers. Meanwhile, this study shows that the mass balance is a promising indicator of climate variations on a considerably larger areal scale than that of the glacier itself.

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