Journal of Glaciology, Vol. 18, No. 78, 1977

A NEW CLIMATIC MODEL FOR GLACIER BEHAVIOR OF THE AUSTRIAN ALPS

By HENRY W. POSAMENTIER

(Department of Geosciences, Rider College, 2083 Lawrenceville Road, Lawrenceville, New Jersey 08648, U.S.A.)

ABSTRACT. Two climatic models are proposed for the fluctuation of Austrian Alpine glacier termini. The glacier record, based on annual observations by the Österreichische Alpenverein, is related to climatological data from the high-elevation Sonnblick-Observatorium. Monthly mean temperature and total precipitation during the ablation season for the concurrent plus preceding eleven years are the variables used in this analysis. The preferred model, mean temperature for June, July and August for the concurrent plus preceding seven years, is inversely related to glacier advance. This model was derived by combining those variables with the highest correlation coefficient relative to the glacier record. Mean lag time between climate and glacier termini response seems to be seven years. The second and less preferred model is derived by multiple regression analysis and includes seven variables of temperature and precipitation. Variation in the glacier behavior record accounted for by the two models is 71% and 67% respectively.

RÉSUMÉ. *Un nouveau modèle climatique pour expliquer le comportement glaciaire des Alpes autrichiennes.* Deux modèles climatiques sont proposés pour expliquer les fluctuations des langues glaciaires des Alpes autrichiennes. Les observations annuelles réalisées par le club Alpin Autrichien ont été rapprochées des données climatologiques recueillies à l'observatoire d'altitude de Sonnblick. Dans cette analyse, on a utilisé comme variables, les températures moyennes mensuelles et les précipitations de la saison d'ablation au cours des 11 dernières années. Le meilleur modèle montre que l'avance des glaciers est inversement liée aux températures moyennes pour juin, juillet et août. Ce modèle fut élaboré en combinant ces variables avec les plus forts coefficients de corrélation résultant des variations glaciaires enregistrées. Le retard moyen entre le climat et la réponse des langues glaciaires semble être de sept ans. Le second modèle moins performant, est issu d'analyses par régression multiple et prend en compte sept variables de température et de précipitation. La proportion des enregistrements du comportement glaciaire dont rendent bien compte les deux modèles, est respectivement de 71% et de 67%.

ZUSAMMENFASSUNG. *Ein neues klimatisches Modell für das Verhalten von Gletschern in den österreichischen Alpen.* Zur Erklärung der Schwankungen der Zungen von Gletschern in den österreichischen Alpen werden zwei klimatische Modelle vorgeschlagen. Das Gletscherverhalten, gegeben durch die jährlichen Beobachtungen des Österreichischen Alpenvereins, wird mit klimatologischen Daten des hochgelegenen Sonnblick-Observatoriums in Beziehung gebracht. In dieser Analyse finden die mittleren Monatstemperaturen und der Gesamtniederschlag während der Ablationsperiode im laufenden und den 11 vorhergehenden Jahren als Variable Verwendung. Das bevorzugte Modell beruht auf einer inversen Beziehung zwischen den Mitteltemperaturen für Juni, Juli und August des laufenden und der 7 vorhergehenden Jahre und dem Gletschervorrücken. Dieses Modell wurde durch Kombination jener Variablen mit dem höchsten Korrelationskoeffizienten bezüglich des Gletscherverhaltens hergeleitet. Die mittlere Verzögerung zwischen Klimaschwankungen und entsprechender Wirkung an den Gletscherzungen scheint 7 Jahre zu betragen. Das zweite und weniger plausible Modell entsteht durch mehrfache Regressionsanalyse und erfasst 7 Variable der Temperatur und des Niederschlages. Die beiden Modelle werden dem beobachteten Gletscherverhalten mit 71% bzw. 67% gerecht.

INTRODUCTION

The hypothesis that glaciers are closely related to variations of weather conditions has been subscribed to for over two hundred years (Walcher, 1773). As Sharp (1960, p. 20) has so concisely stated, glaciers ". . . are utterly dependent upon elements of the climatic environment for birth and for sustaining life". Many workers, especially during the past half century, have provided climatic models to account for glacier behavior (Wagner, 1929, 1940; Billwiller, 1931, [1950]; Wallén, 1949; Ahlmann, 1953; Hoinkes and Rudolph, 1962; Hoinkes, 1968).

Rather than relating glacier behavior to synoptic weather patterns, this report examines the Austrian glacier record *vis-à-vis* the Austrian climatic record utilizing multiple regression analysis techniques. Each year since the late 19th century, observations on the state of a large number of glaciers in the Austrian Alps have been made under the auspices of the Austrian Alpine Club (*Österreichische Alpenverein*). These records have been compiled by Patzelt (1970) for the years 1890–1969. The meteorological data used in this study are taken from observations made at the Sonnblick-Observatorium (Steinhauser, 1938; Clayton and Clayton, 1947; U.S. Weather Bureau, 1959; U.S. Environmental Data Services, 1966) maintained since 1887 by members of the Sonnblick-Sektion.

Climatic record

As Rumney (1968) has noted for mountain regions, climatic change is distinctly observable from base to summit. He further states that given the complexity of mountain climate the one phrase which may be used to describe the essence of such climate is "extreme differentiation". With this in mind it must be noted that with changes of climate so sudden and so great over small areas, climatic data from local observatories must be scrutinized carefully before use in any regional analysis. In general, as meteorological data gathered at valley stations describe valley climate only, it is not desirable to extrapolate climatic conditions from the valley to higher elevations where weather may be radically different. The opposite holds true as well; ideally in order to maintain proper control, a network of meteorological stations should be established over the area surrounding each glacier studied. This is, however, both an impractical and unrealistic approach in the light of the Alpine environment, and moreover may still not account for some localized climatic phenomena. Thus, the Sonnblick-Observatorium was chosen as most representative of the Austrian glacierized regions both because of its high Alpine location and also its length of continuous operation.

This observatory is located at the summit of the Sonnblick, situated in the central part of the Eastern Alps, south-central Austria, lat. 47° 03′ N., long. 12° 57′ E., at an elevation of 3 106 m, some 900 m above the tree line (Fig. 1). Although this high-elevation station records climatic parameters whose seasonal fluctuations will be roughly the same over much of the glacierized Austrian Alps, allowances must nonetheless be made for localized weather conditions which may bias the data from time to time. In addition, such factors as wind speed and direction, relative humidity, hours of sunshine, number of cloudy days, and perhaps barometric pressure, examined on a daily basis, may vary greatly over short distances. Nevertheless, other parameters such as mean monthly temperature and total monthly precipitation trends will not vary greatly over this area and will represent reliable trends for the region.

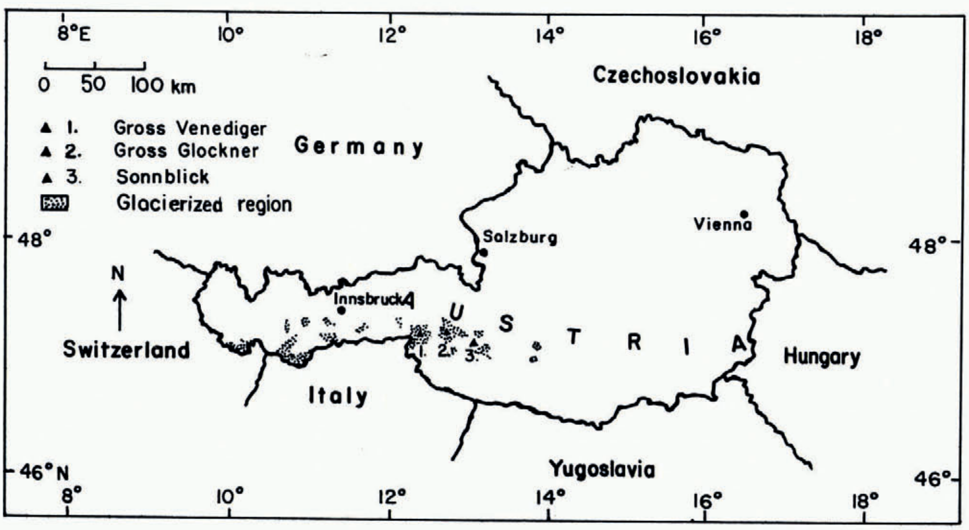

Fig. 1. Location of Sonnblick meteorological observatory and principal Austrian glacierized regions.

The glacier record

As shown in Figure 2 the state of Austrian Alpine glaciers, 1898–1969, is described in terms of the percentages of glaciers advancing (henceforth referred to as AGL) or glaciers advancing or stationary (henceforth referred to as ASGL). The number of observed Austrian glaciers varies from a low of 18 in 1902 to a high of 95 in 1969 with an average of 54 per year. The glaciers observed are principally of the warm-temperate valley type.

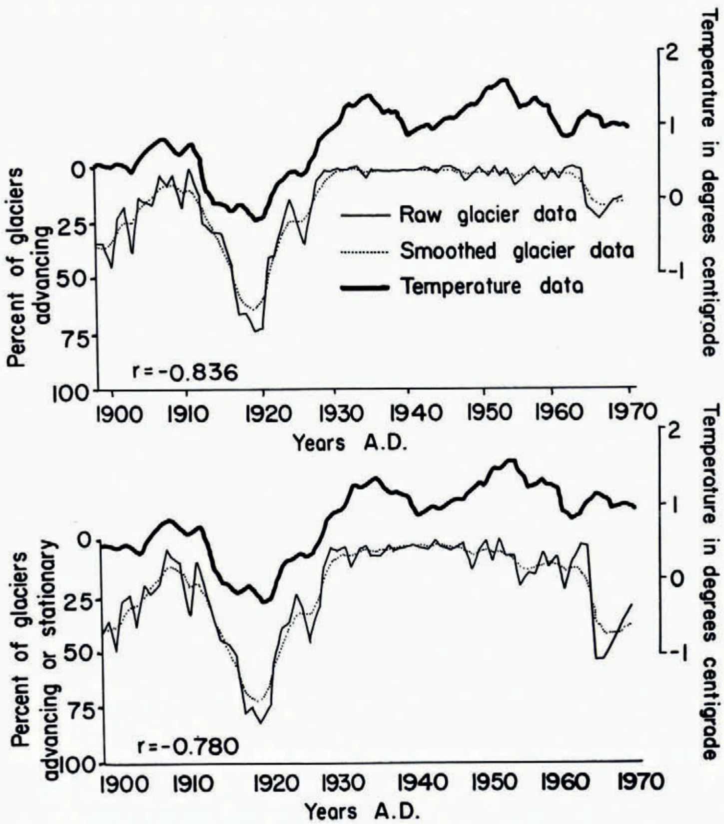

Fig. 2. Austrian Alpine glacier behavior with mean temperature of June, July and August of the concurrent plus preceding seven years (1898–1969) at Sonnblick Observatorium.

From the glacier record only one distinct period of glacier advance is noted. Only during the period 1917 through 1920 were more than 50% of the glaciers advancing each year. Less marked periods of advance are noted in 1898 to 1904, 1913 to 1916, 1921, 1927, and 1965 to 1966. The period 1928 through 1964 is marked by a strong retreat of glacier termini when an average of 92% were retreating each year.

Data analysis

Glacioclimatology

Air temperature and precipitation in the summer months are the variables most commonly correlated with glacier behavior. This selection is not one of preference but rather one of convenience and necessity as other variables have not been recorded regularly for a long

https://doi.org/10.3189/S0022143000021511 Published online by Cambridge University Press

enough period of time. In this study these two variables again are used to the exclusion of any others because monitoring of other climatic parameters has been erratic and incomplete.

A total of 144 climatic variables was employed; six were monthly mean temperatures and six were total monthly precipitation, May through October. The remaining included the twelve aforementioned variables of temperature and precipitation for each year up to and including eleven years prior to the concurrent year. The period May to October is chosen because it is approximately the potential ablation season for Alpine glaciers. As Hoinkes (1968) correctly states the critical period in the life of a warm-temperate glacier which determines whether advance or retreat will occur is the ablation period, May through late September. Although glacier advance may be supported by heavy winter snows as occurred in 1920, even heavy winter snows cannot stop glacier retreat caused by sunny and dry summers, a situation which occurred in 1950. Also, because glacier behavior is affected by previous years' climate, data for the period eleven years prior to the concurrent year are included. In addition to these 144 variables, new variables were computed from the combination of two or more of the original variables.

In general there exists an inverse relationship between the percent of glaciers advancing and mean ablation-season temperature whereas there exists a direct relationship between the percentage of glaciers advancing and mean ablation-season precipitation. Because a stationary glacier also reflects to a high degree a relative deterioration in climate during an episode of prolonged general retreat, the percent of glaciers advancing or stationary is considered and compared to the climatic record as well.

Multiple regression analysis

In order to establish a climatic model for glacier behavior, multiple regression analysis is used to provide a regression model which may be more satisfactory than that provided by analysis involving only one independent variable (Fritts, 1962). A linear model of the conventional form is used:

$$Y = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n$$

where Y is the dependent variable, x_1 through x_n are the independent variables, and b_0 through b_n are the regression coefficients. Independent variables included in the analysis were the 144 climatic variables discussed above. Of all the different equations possible there is one which affords the greatest significant reduction in the variance of the dependent variable. In the step-wise procedure this equation is determined by taking one variable into the equation at a time. The variable chosen is that which will result in the greatest reduction in the variance of the dependent variable. This step-wise operation continues until such time as the continuous addition of variables to the equation does not significantly reduce the variance of the independent variable. In order to determine what combination of variables accounted for most of the variation in the glacier behavior record, step-wise multiple regression analysis was applied yielding the following equation:

Y percent of glaciers advancing $= 0.233 - (0.287 \times$ mean July temperature 5 years prior to the concurrent year$) - (0.160 \times$ mean July temperature 1 year prior to the concurrent year$) - (0.219 \times$ mean August temperature 2 years prior to the concurrent year$) + (0.090 \times$ total October precipitation 2 years prior to the concurrent year$) - (0.270 \times$ mean August temperature 4 years prior to the concurrent year$) - (0.169 \times$ mean June temperature of the concurrent year$)$.

Although the climatic model for glacier behavior thus produced is by no means the ideal model, 67% of the variation in the glacier-behavior record is nevertheless accounted for.

Relationships between computed variables and glacier behavior

The percentage of glaciers advancing and the percentage of glaciers advancing or stationary show consistently strong relationships with monthly mean summer temperatures though more so with those of previous years than to those of the concurrent one. Hoinkes (1968) has noted that glaciers respond less to the conditions of an individual year but rather to the mean conditions of several consecutive years. Thus, the results of this study are to be expected; that is, that a real relationship is shown between glacier behavior and the climatic record for the summers one, two, and even eleven years prior to the concurrent year. Such a relationship necessarily gives rise to strong serial dependence in the glacier series and is clearly indicated by the autocorrelation coefficient with a lag of one year, $r_1 = 0.852$, indicating that the AGL in one year is to a great degree dependent on the AGL of prior years. Whereas it is true that glacier behavior is related to the mean temperature of individual months, as no single month may be singled out as the most critical, it is usually more meaningful to compare glacier behavior to groups of critical months. The months whose mean temperatures are most closely related to glacier behavior are June, July and August, henceforth referred to as the "key months".

The record of mean summer temperature (May, June, July, August, September, October) of the concurrent year is clearly related to AGL and ASGL with a correlation coefficient $r = -0.319$ and $r = -0.312$ respectively, both significant to the 0.01 level, although not as strongly as the mean temperature of the key months with $r = -0.427$ and $r = -0.459$ for AGL and ASGL respectively, both significant to the 0.001 level. This latter relationship is graphically shown in Figure 3. When glacier behavior is related to the mean temperature of the concurrent plus the previous year's key months a stronger relationship becomes apparent with $r = -0.565$ and $r = -0.578$ for AGL and ASGL respectively, both significant to the 0.001 level. The relationship between glacier behavior and the mean monthly temperature for the key months of the concurrent plus previous years becomes stronger as more previous years are added to the initial variable. Figure 2 illustrates the relationship between AGL and ASGL and the mean temperature for the months of June, July and August for the concurrent plus the preceding seven years where the highest r is attained. As more previous years are added the value of r drops off gradually. Thus when AGL and ASGL are compared to this variable, $r = -0.836$ and $r = -0.780$ respectively, both significant to the 0.001 level. Accounting for 70% and 61% of the variance in AGL and ASGL respectively, this variable is seemingly an excellent indicator of the behavior of Alpine glaciers of the type observed in the Austrian Alps. The mean lag time for the average Austrian glacier is thus approximately seven years.

The record of glacier behavior also differs directly with fluctuations of mean precipitation. The key months here are seemingly August and September. Winter precipitation, for the reasons discussed above, are not considered in this study. During August and September, usually the last two full months of the ablation season, maximum melting takes place over the entire glacier. Long-wave radiation from the snow-free surrounding valley walls will reach a maximum during this period and the current year's snow mantle will have been melted from much of the glacier exposing the previous years' snow, firn and ice, with their relatively low albedo, thus accelerating ablation during this period. If, however, precipitation is great during August and September, such precipitation, commonly occurring as snow at least in the accumulation zone, impedes subsequent ablation because of its relatively high albedo, whereby much solar radiation is reflected at the glacier surface. In addition, the reduced long-wave radiation from the surrounding valley walls also covered by snow, will result in further lessening of glacier ablation.

Curiously, however, no clear relationship seems to exist between glacier behavior and concurrent ablation-season precipitation; rather, the cause and effect relationship between

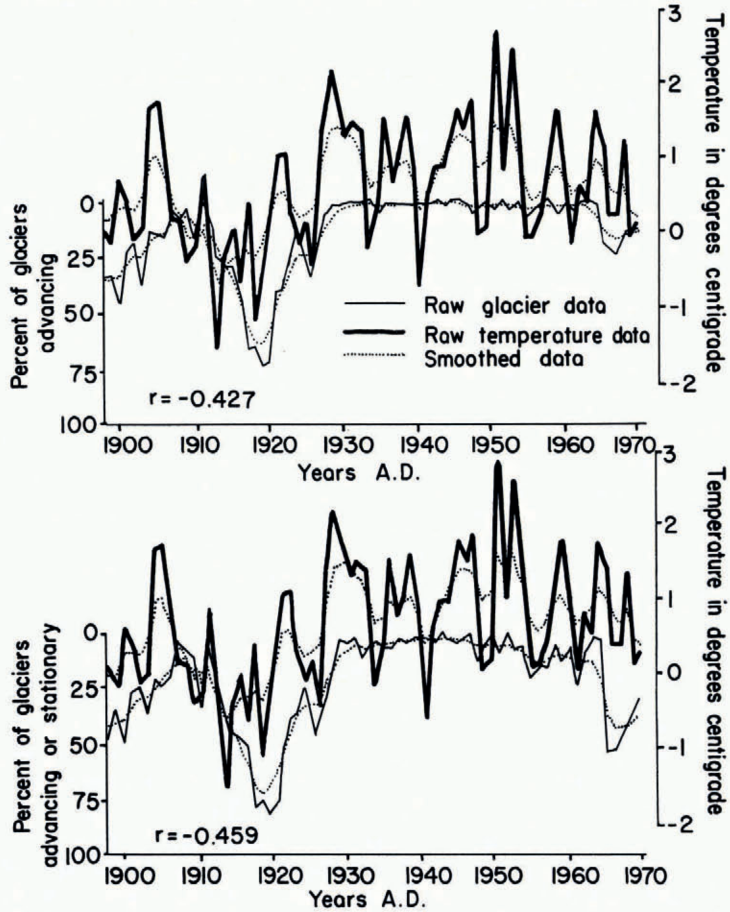

Fig. 3. Austrian Alpine glacier behavior with mean temperature of June, July and August of the concurrent year (1898–1969) at Sonnblick Observatorium.

AGL and ASGL and precipitation involves a lag of at least four years for the effects of September precipitation to take hold and at least seven years for August precipitation. Thus r for total concurrent August and September precipitation and the AGL and ASGL series is 0.055 and 0.177 respectively, neither statistically significant, and only becomes significant to the 0.001 level with the total August and September precipitation for the year seven years prior to the concurrent year where $r = 0.390$ and 0.362 for the AGL and ASGL series respectively. Again keeping in mind that climate has a cumulative effect on glacier behavior, a significant relationship (to the 0.001 level) is shown to exist between the AGL and ASGL series and the mean total August and September precipitation for the years seven years prior through eleven years prior to the concurrent year with $r = 0.517$ and 0.474 respectively. To explain this phenomenon, the concept of glacier regimen again must be considered. Snowfall at any time of year has a positive effect on the glacier budget. Summer snowfall in this regard has a twofold role; first, it adds to the overall nourishment of the glacier and second, it impedes ablation by providing a protective covering as a result of its relatively higher albedo. New variables comprised of combinations of precipitation and temperature variables then are computed and are observed not to have as high r values with the glacier series as the previously considered temperature variables alone.

Proceeding under the assumption that glaciers will respond more dramatically to extreme highs and lows of given variables, the glacier record is correspondingly examined. Those years in which AGL was greater than or equal to 6% are initially considered in order to determine which variables have the greatest influence upon glacier behavior during these glacially active years. The rationale is that, as climate ameliorates, AGL will become zero; as it continues to ameliorate AGL stays at zero, thus, during that stretch of years, one summer with radically warmer and dryer climate or cooler and moister climate although insufficient to cause glacier re-advance, will not be reflected by the curve of AGL. Nevertheless, in this analysis, no new relationships between any variables and AGL became apparent. This was also the situation when the years of extremes (plus or minus one standard deviation) of selected variables were considered.

Prediction of glacier behavior

In order to predict the variation of glacier behavior from the variation of independent variables an equation in the general form (Sokal and Rohlf, 1969, p. 424):

$$s_{\hat{y}} = \left\{ s^2{}_{Y \cdot X} \left[\frac{1}{n} + \frac{(X_i - \bar{X})^2}{\Sigma x^2} \right] \right\}^{\frac{1}{2}}$$

is used where $s_{\hat{y}}$ is the standard error of estimate of an estimated Y for a given value of X, $s^2{}_{Y \cdot X}$ is the unexplained mean-square or residual variation between an estimated and an observed Y, n is the number of observations, X_i is a given value of X, $\bar{X}$ is the mean value of X, and Σx^2 is the sum of squares of deviations. $s_{\hat{y}}$ then is used to compute the confidence limits for Y_i:

$$L = Y_i \pm t s_{\hat{y}}$$

where L is the confidence limit and t is the Student's t-distribution. By choosing the appropriate value of t, the confidence limits may be computed.

Confidence limits of 99% for estimated variation of AGL and ASGL based on the variation of mean June, July and August temperature for the concurrent plus the preceding seven years are shown in Table I. Thus, for example, when this mean temperature is −2°C, 97±16% of Austrian glaciers may be expected to advance, while when the mean temperature is +0.75°C,

Table I. Prediction of glacier behavior from the variation of mean temperature of June, July and August of the concurrent plus preceding seven years

Mean temperature of June, July and August for the concurrent plus preceding seven years °C	*AGL** %	*ASGL** %
−2.00	97.2±16.3	109.0±21.1
−1.50	80.8±13.1	91.7±17.0
−1.00	64.4±10.0	74.3±12.9
−0.50	48.0± 7.0	57.0± 9.0
0.00	31.6± 4.3	39.6± 5.6
0.50	15.2± 3.1	22.2± 4.1
1.00	−1.2± 4.7	4.9± 6.1

* Values greater than 100% or less than 0% are beyond the boundary values of AGL and ASGL and are disregarded as they reflect an invalid physical situation.

https://doi.org/10.3189/S0022143000021511 Published online by Cambridge University Press

$7 \pm 4\%$ of Austrian glaciers may advance. Only this set of confidence limits is presented here because the variation in the AGL and ASGL series accounted for by this variable is approximately equivalent to that accounted for by the climatic model derived by multiple regression analysis and provides a more reasonable and workable model.

Conclusions

It has long been recognized that glaciers are sensitive indicators of climatic change. This study is directed at clarifying this relationship by examining the Austrian glacier record *vis-à-vis* the climatic record from the high-elevation meteorological Sonnblick-Observatorium. The following are some major glacio-climatological conclusions suggested by statistical analyses.

(1) The record of glacier behavior expressed as the percentage of glaciers advancing or the percentage of glaciers advancing or stationary is shown to be highly autocorrelated. This high degree of autocorrelation is seemingly caused by the dependence of glaciers upon the weather of successive summers rather than simply the concurrent one.

(2) A climatic model accounting for 67% of the variation of Austrian glacier behavior is derived by multiple regression analysis. The variables used included temperature and precipitation for the months May through October, as these approximate the ablation season for this region. The resulting model, however, while mathematically and theoretically valid is neither workable nor realistic.

(3) Significant correlation was shown to exist between glacier behavior and mean temperature of three key months: June, July and August. The dependence of glacier behavior on previous years' weather is illustrated by the increase of the correlation coefficient when glacier behavior is related to the mean temperature of the concurrent year's key months plus that of the preceding year. The correlation between these two variables is seemingly enhanced when additional preceding years are included in the latter variable. A peak is reached with the addition of the preceding seven years' key months' temperatures to that of the concurrent year. Therefore, this composite variable is a reliable indicator and potential predictor of future glacier behavior. For the average Austrian glacier, the mean lag time is shown to be approximately seven years.

(4) Although no clear relationship exists between glacier behavior and concurrent ablation-season precipitation, glacier behavior is affected by past ablation-season precipitation, the key months being August and September. The peak effects of total August and September precipitation are felt after a lag of approximately seven years.

(5) No new relationships between weather and glacier behavior became apparent when only years of extremes of variables were chosen for analysis. Likewise, when only glacially active years were chosen, no new relationships were shown.

Acknowledgements

This work was funded by a Fulbright-Hays Fellowship and by a Grant-in-Aid of Research from the Society of Sigma-Xi. I would like to thank E. H. Muller for many stimulating discussions and constructive criticisms on this and related problems. Thanks are also due to the aides at the computer center of Syracuse University for their assistance in computer programming.

MS. received 2 February 1976 and in revised form 22 June 1976

REFERENCES

Ahlmann, H. W. 1953. *Glacier variations and climatic fluctuations*. New York, American Geographical Society. (Bowman Memorial Lectures, Ser. 3.)

Billwiller, R. 1931. Temperatur und Niederschlag im schweizerischen Alpengebiete während des letzten Gletschervorstosses. *Annalen der Schweizerischen Meterologischen Zentralanstalt* [for] 1930, Bd. 67, Anhang No. 6.

Billwiller, R. [1950.] Die kurzfristigen Schwankungen der Alpengletscher und ihre Ursachen. *Union Géodésique et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique. Assemblée générale d'Oslo, 19–28 août 1948*, Tom. 2, p. 323–28. ([Publication No. 30 de l'Association Internationale d'Hydrologie Scientifique.])

Clayton, H. H., *and* Clayton, F. L. 1947. World weather records, 1931–1940. *Smithsonian Miscellaneous Collections*, Vol. 105.

Fritts, H. C. 1962. An approach to dendroclimatology: screening by means of multiple regression techniques. *Journal of Geophysical Research*, Vol. 67, No. 4, p. 1413–20.

Hoinkes, H. C. 1968. Glacier variation and weather. *Journal of Glaciology*, Vol. 7, No. 49, p. 3–19.

Hoinkes, H. C., *and* Rudolph, R. 1962. Variations in the mass-balance of Hintereisferner (Ötztal Alps), 1952–1961, and their relation to variations of climatic elements. *Union Géodésique et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique. Commission des Neiges et des Glaces. Colloque d'Obergurgl, 10–9—18–9 1962*, p. 16–28. (Publication No. 58 de l'Association Internationale d'Hydrologie Scientifique.)

Patzelt, G. 1970. Die Längenmessungen an den Gletschern der österreichischen Ostalpen 1890–1969. *Zeitschrift für Gletscherkunde und Glazialgeologie*, Bd. 6, Ht. 1–2, p. 151–59.

Rumney, G. R. 1968. *Climatology and the world's climates*. New York, Macmillan Co.

Sharp, R. P. 1960. *Glaciers*. Eugene, Oregon, University of Oregon Press.

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

Steinhauser, F. 1938. *Die Meteorologie des Sonnblicks*. Wien, Sonnblick-Verein, Springer.

U.S. Environmental Data Services. 1966. *World Weather Records*, 1951–60, Vol. 2.

U.S. Weather Bureau. 1959. *World Weather Records*, 1941–50.

Wagner, A. 1929. Untersuchung der Schwankungen der allgemeinen Zirkulation. *Geografiska Annaler*, Årg. 11, Ht. 1, p. 33–88.

Wagner, A. 1940. *Klimaänderungen und Klimaschwankungen*. Braunschweig, Friedrich Vieweg und Sohn.

Walcher, J. 1773. *Nachrichten von den Eisbergen in Tyrol*. Wien, Joseph Kurzböck.

Wallén, C. C. 1949. The shrinkage of the Kårsa Glacier and its probable meteorological causes. *Geografiska Annaler*, Årg. 31, Ht. 1–4, p. 275–91.