Our measurement on the north dome of the Barnes Ice Cap was made in hole Nooo at lat. 70° 01′ N., long. 73° 25′ W. at an elevation of approximately 1 115 m. Due to problems with the drill and to approaching bad weather, the hole reached a depth of only 8.6 m and measurements had to be made within 3 h of the time the hole was completed. Thus, thermal equilibrium clearly had not been re-established but measurements over a period of nearly 2 h at the bottom of the hole again provide a basis for extrapolating to equilibrium. The equilibrium temperature at 8.6 m is estimated to be −11.7±0.3°C (Fig. 2). For comparison, the temperature at a depth of 17 m in hole Tooo at an elevation of 892 m on the south dome of the ice cap is −7.67°C. Tooo was drilled in July 1973 and was measured 1 year later. Hole Nooo penetrated highly permeable firn containing scattered ice lenses, indicating that this hole was in the percolation zone of the accumulation area. In contrast, at depths greater than 2–3 m, hole Tooo was in superimposed ice with scattered firn layers characteristic of the soaked zone. The amount of percolating melt water at Tooo is thus greater than at Nooo, and heat released by refreezing of this water is responsible for most of the temperature difference between these two sites. Based on numerical modeling of temperature profiles in Tooo and five additional holes at lower elevations on the south dome, the mean annual temperature at Tooo is estimated to be about −13.0±0.5°C (Hooke, 1976[a]; unpublished data). The mean annual temperature at Nooo is probably only a degree or so colder.

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Department of Geology and Geophysics,
University of Minnesota,
Minneapolis,
Minnesota 55455, U.S.A.
15 September 1977

ROGER LEB. HOOKE
BRUCE R. KOCI

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SIR,

On the non-linearity of glacier length response to climatic changes: comments on a paper by H. W. Posamentier

IN a recent paper in the *Journal of Glaciology*, Posamentier (1977) speaks of a new climatic model for glacier behaviour. This is indeed a title that will attract the attention of the scientific community and it nourishes the hope that, at least for the Eastern Alps, there is now a way of modelling or predicting the intricate relations linking glaciers and climate.

When reading the paper, however, one becomes aware that it does not deal with the physical interaction of the atmosphere with glaciers and their dynamic response, nor with glacier behaviour in the complex sense but with a linear regression of the percentage of Austrian glaciers advancing or retreating (out of the varying number counted each year) as a variable dependent on several combinations of precipitation and temperature values as recorded at Sonnblick observatory in the Hohe Tauern.

Although it may be felt by some readers that to speak of this as a climatic model is an exaggeration, it is worthwhile investigating the physical significance of relating any climatic variable or parameter to glacier lengths, of whose variations there exist long records. There is no doubt that we should make the best possible use of the meticulous work of past generations which is continued up to date and includes length measurements as well as the work relating precipitation, heat budget, mass budget, and dynamic response to changes in glacier length. Climate influences the first two members of this chain, but the reaction of the glacier terminus to mass balance changes is complicated by the dynamics of ice flow.

If a glacier has reached a dynamically steady state then small changes of mass balance will result in changes of the terminus position that can be interpreted in terms of climatic variables provided that the effects of accumulation and ablation (heat budget) can be separated by means of independent information.

The number of Austrian glaciers used for these statistics varies from year to year (Patzelt, 1977). They include small and large glaciers, valley and plateau types, a glacier that is known to surge, glaciers in the dry interior valleys and those of the wet marginal regions (e.g. Ötztal versus Tauern), in short, glaciers of many different degrees of disequilibrium. The physical interrelation of each of these glaciers' length to climate is different. Glaciers that differ in accumulation, ablation (heat budget), and topography may seem to furnish an ideally unbiased statistical group, but in reality they are not apt to yield optimum information when lumped together over periods of time in which their spectral distribution varies.

The response time, i.e. the period during which a glacier terminus is adjusting to a new equilibrium size, is determined by strain-rate and diffusion, which in turn depend on length, thickness, and topography of the glacier. The adjustment to a new size may still be taking place while the first reaction to a new change in mass balance is being felt at the terminus with a time lag of about a quarter of the period of that change. Depending on the respective frequencies and amplitudes of a series of mass-balance fluctuations, these will result in a complex pattern of advances or retreats that is governed by the variables mentioned above (see, e.g. Nye, 1961, or Paterson, 1969). The variety of reactions is well demonstrated by the behaviour of Hintereisferner, Kesselwandferner, and Vernagtferner, which all lie within 10 km of each other. From 1974–75 Hintereisferner retreated 10 m, whereas Kesselwandferner advanced 19 m (Kinzl, 1976). While Vernagtferner is presently retreating, its ability to surge is well documented for the past centuries (Hoinkes, 1969); its dynamic response to changing climate was modelled by Kruss (1976).

The indiscriminate use of all observed Austrian glaciers for the establishment of a lag time therefore is a linearization which is bound to decrease the information content of the length records. It also introduces an obvious bias that may be reversed in the coming decades. Presently, the tongues of major glaciers are receding, regardless of the sign of the glaciers' actual mass balance, in response to the climatic conditions of the forties and fifties whereas smaller ones are advancing after recent mass gain.

Considering the inhomogeneities in the statistical population due to the different types of glaciers, and in the time domain due to both different response times of the glaciers and a degree of disequilibrium from past climatic conditions that varies within the sampling period, one should expect the correlation to improve with a subdivision of the sample. It would therefore seem likely that an improvement of the correlation would be obtained if the statistics were subdivided according to glacier size and time.

One could, of course, try to describe the average Austrian glacier, neglecting all the difficulties mentioned above. An average glacier would be well applicable to a number of problems like long-term hydrological forecasting. This concept of an average, however, would require a time scale that is larger than any of the periods of climatic changes or of glacier response in question. To be applicable it should be restricted to small glaciers, so that a subdivision of the sample is again wanted.

The relation between Sonnblick climate and length variations as treated by Posamentier is to a large degree non-linear. Therefore, the climatic change used to predict length variations, or the values of the latter used to infer climatic changes, must be small in order to apply a regression based on unweighted spectral averages, so small that it may well be that random changes such as induced by geology of the glacier beds may become predominant. The investigation should have first dealt with the problem of how Austrian glaciers behave when there is no climatic change whatsoever. Then this statistical exercise would have rested on some kind of physical basis and would have led to more fruitful discussions than the present one.

A word of caution against the selection of variables by means of stepwise regression analysis is quoted from Draper and Smith (1966, p. 172): "We believe this" (the stepwise regression analysis) "to be the best of the variable selection procedures . . . however it can easily be abused by the 'amateur' statistician . . . sensible judgment is required in the initial selection of the variables and in the critical examination of the model through examination of residuals. It is easy to rely too heavily on the automatic selection performed in the computer."

Previous studies that have investigated the climate–glacier relationship on a statistical rather than a purely physical basis (Hoinkes and Steinacker, 1975) have found correlation coefficients that ranged from −0.85 to −0.94 depending on the degree of refinement of parameterization. The quantities used were the mass balance of one glacier and a combination of temperature and precipitation at the nearest valley station.

The correlation coefficients mentioned by Posamentier (1977) again show the loss of information that is caused by the correlation of a large regional and physical variety of glacier length changes with climatic parameters of one single station. Even over a small distance like that from Hohe Tauern to Ötztal Alps the precipitation regime changes markedly because of the central position of the latter. This problem has long been treated by alpine climatologists and can easily be verified by the correlation of July precipitation values of Sonnblick and Vent (Ötztal, 1 900 m). Using the data of 1936–69 (*Jahrbücher der Zentralanstalt für Meteorologie und Geodynamik* (Wien), 1936–69; Lauffer, unpublished) one finds for a correlation of July precipitation Vent/Sonnblick (1936–69): $r = 0.16$. In view of this poor correlation one must admit that yearly mass-balance values of the glaciers in the Ötztal Alps, or the interaction of the atmosphere with the glaciers in that area, is poorly represented by records of precipitation at Sonnblick. This example seems sufficient to show that a subdivision of glaciers not only according to size and bed-topography but also according to climatic regions is physically justified and promotive of higher statistical correlation even of such ancillary quantities as length and precipitation.

Finally, we are left again with the question: What shall we do with the length records? What exactly do they tell us except how many glaciers of those observed were advancing? Variations of an individual glacier can within certain limitations be linked to climatic variations from the study of this century's climatological and glaciological records. The yearly length measurements on the Alpine glaciers are an undisputable and invaluable basis for the reconstruction of the climate of past centuries. Their use in bulk correlation to one station's temperature and precipitation will, however, not do justice to the present state of glacial meteorology.

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Institut für Meteorologie und Geophysik,
Universität Innsbruck,
Schöpfstrasse 41,
A-6020 Innsbruck, Austria
11 October 1977

M. KUHN

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Sir,

The origin of the term "rock glacier"

During the course of our work on rock glaciers, a minor but unclear point of nomenclature emerged. Numerous researchers (Wahraftig and Cox, 1959; Potter, 1972; White, 1976; Corte, 1976) have all followed suit in attributing the first usage of the term "rock glacier" to Capps (1910). Capps himself contributed to this misunderstanding of first usage when he stated (Capps, 1910, p. 359–60), "The special agents with which I wish to deal at present . . . I have called *rock glaciers*".

While other terms were used in earlier literature, the term "rock glacier" first appeared in print in 1905 (the internal text date is 1903) in an indirect manner. In describing the occurrence of rock glaciers in the Silverton, Colorado, area, Cross and Howe (1905, p. 25) wrote, "So noticeable was this [apparent viscous flow] that in the field they were spoken of as 'rock glaciers' and upon the map received the name 'rock streams' ". Presumably the term "rock glacier" was used in the field at this time among some of the personnel of the United States Geological Survey of which Cross, Howe, and Capps were all members. Cross and Howe either voluntarily changed their usage of the term "rock glacier" to "rock stream" or an editorial change was suggested by someone else. Apparently Capps was not so restricted and has received most of the credit for first usage of the term.

Department of Geography,
University of Nebraska—Lincoln,
Lincoln,
Nebraska 68588, U.S.A.
John R. Giardino

Department of Geography and Geology,
University of Nebraska—Omaha,
Omaha,
Nebraska 68132, U.S.A.
John F. Shroder, Jr.

15 September 1977

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