Annals of Glaciology 14 1990

QUANTITATIVE APPROXIMATION OF MOUNTAIN GLACIAL CLIMATES

by

William W. Locke

(Department of Earth Sciences, Montana State University, Bozeman, MT 59717, U.S.A.)

ABSTRACT

The winter precipitation at the equilibrium line altitude of a wide selection of modern mountain glaciers is well explained ($r^2 = 0.81$, $n = 25$) by multiple regression using summer temperature and the logarithm of continentality (distance from a moisture source) as independent variables. Continentality serves as a proxy for inland decreases in energy input through longwave radiation and condensation and increasing energy losses through evaporation and sublimation. Winter precipitation in presently inaccessible areas and former precipitation across broad regions can thus be estimated accurately from two simple variables.

INTRODUCTION

Deposits of glaciers which were more extensive in the past than at present have long been recognized as indicators of a climate which was formerly wetter and/or colder than it is now. What has been lacking, however, is a quantitative method for interpreting paleoclimate from such indicators. The problem lies in the difficulty of assigning a unique climate to the existence of present glaciers; thus by analogy, the difficulty in assigning a unique climate to the existence of past glaciers.

The climatic setting of modern glaciers has been addressed for individual glaciers by many detailed field studies. Climate, in this context, includes all measurable variables of mass and energy exchange, such as air temperature, humidity, cloudiness, wind velocity, and type and amount of precipitation. Such data are too detailed for generalization to the problem of glacial climates. The other extreme includes the characterization of glacial climates by as few as two variables, generally representing accumulation (such as winter precipitation) and ablation (such as summer temperature).

WORK TO DATE

Since Ahlmann (1924), workers have characterized glacial environments in terms of the accumulation (= ablation) at the equilibrium line altitude (ELA) and the ablation season temperature, also at the ELA. In any restricted area there is a strong relationship between these two variables. This perhaps is best documented in the data from Norway (Sutherland, 1984, figure 4) and the eastern Alps (Kerschner, 1984, figure 1), where glaciers occur as a highly predictable function of summer temperature and winter precipitation. However, a global summary of glacial climates (Loewe, 1971) shows a far weaker correlation between those two variables. Although other variables have been considered (cf. Khodakov, 1975; shortwave radiation balance), Loewe (1971) suggested that the discrepancy could be explained by the location of the glaciers studied, particularly their continentality (distance from a major moisture source). This paper tests the hypothesis that glacial climate is controlled by continentality and suggests an application of the result: a quantitative approximation of former mountain glacial climates.

DATA

The data used in this analysis (summer temperature, winter precipitation, continentality, and latitude; Table I) are those of Loewe (1971, table I) and Sutherland (1984, scaled from his figure 4), where the named glaciers could be located. (Some of the original literature is not yet available to the author.) These data are less than optimal for this analysis for several reasons. They are severely skewed in favor of maritime environments. They include climatic data sets which are of varying lengths, thus are not necessarily comparable. Similarly, they utilize average ablation-season temperature rather than sharing common months of record — again leading to questionable correlation. However, no consistent bias other than that towards maritime environments is evident, thus the data should yield accurate results of low precision rather than biased results of high (implied) precision.

ANALYSIS

Two analytical approaches were used: (1) to formulate an *a priori* hypothesis and test its statistical validity and (2) to use exploratory statistics to formulate additional hypotheses (testable only by the generation of additional data). The data were analyzed using MSUSTAT (developed by R. E. Lund, Montana State University, Bozeman, MT 59717) subroutine MREGRESS (multiple regression, Snedecor and Cochran, 1980). Both approaches share the designation of winter accumulation as the dependent variable. This designation is arbitrary, but not capricious. In the regionalization of montane climate it has been demonstrated that temperature is far more regionally consistent than precipitation (e.g. Mitchell, 1969; Locke, 1989). It appears appropriate to designate one variable (precipitation) as dependent for the remainder of the analysis because the actual cause-and-effect relationship between temperature and precipitation at glacial equilibrium line altitudes is unclear.

The *a priori* hypothesis is that the winter precipitation (= summer ablation) at the ELA of modern glaciers is a linear function of the summer temperature at that level and a logarithmic function of continentality. The linear model for control by temperature represents the logical equation of available heat energy to mass loss through melting. It does not recognize non-linear effects such as an increasing proportion of energy loss to sublimation in cold settings and evaporation in dry settings. The incremental effect of continentality on glacial ELAs decreases rapidly with increasing distance inland (e.g. Porter and others, 1983), thus continentality is unlikely to be a linear control on necessary precipitation.

The exploratory hypotheses included transformations of the data set to optimize regression efficiency and explanation. Because both precipitation and continentality are skewed, transformation is required to maintain maximum confidence in the regression procedure. Box and Cox (1964) suggest a procedure for optimizing the distribution of the dependent variable. This procedure suggests that a square root or logarithmic (base 10) transformation is appropriate

TABLE I. MODERN GLACIER CLIMATIC AND GEOGRAPHIC DATA

Glacier	Summer T. °C	Winter PPT cm H_2O	Continentality km	Latitude °
	(after Loewe, 1971)			
Arapahoe	7.0	250	2000	40.0
Barnes Ice Cap	0.0	55	150	70.5
Blue	7.0	350	75	47.8
Franz Josef Land	−1.5	30	50	80.2
Froya	−1.0	30	120	74.0
Gilman	−1.5	10	20	81.0
Hintereisferner	2.5	85	200	46.8
Hoffellsjökull	4.0	230	30	64.5
Lewis	−0.5	30	150	71.0
Penny Ice Cap	−2.0	40	100	67.0
Peyto	2.0	180	650	51.7
Place	4.5	170	275	50.4
Sonnblick	2.0	120	200	47.1
Storglaciären	2.5	125	200	67.9
Styggedal	0.5	110	175	61.5
Tuyuksu	1.5	35	3000	43.0
	(after Sutherland, 1984)			
Folgefonni	3.2	270	60	60.0
Engabreen	3.6	325	20	66.6
Alfotbreen	3.7	380	30	61.8
Nigardsbreen	2.75	225	120	61.7
Tunsbergdalsbreen	2.2	220	100	61.5
Hardangerjökulen	2.2	190	130	60.5
Storbreen	1.5	140	150	61.6
Hellstugubreen	0.7	110	160	61.6
Grasubreen	−0.7	75	165	61.6

for winter precipitation. Similarly, Box and Tidwell (1962) suggest an analysis for appropriate transformation of independent variables. Log_{10}continentality is optimum. Accordingly, all permutations of $\log_{10}$ and untransformed winter precipitation and continentality were used with summer temperature to maximize explanation of the precipitation variable.

The final independent variable used in the analysis was latitude and its transformation, cosine (latitude). The strong correlation between latitude and summer temperature and between latitude and continentality guarantees that as the *only* independent variable, latitude will be a significant predictor of winter precipitation. However, as an *additional* variable it will be of minimal significance. This prediction is fulfilled by the analyses.

RESULTS

The results of the analyses (Table II, Fig. 1) confirm both the reported correlations of Sutherland (1984) and Loewe (1971) and the *a priori* hypothesis. In a limited geographic area (e.g. Sutherland, 1984; Norway), winter precipitation at the ELA is well-predicted by summer temperature at the ELA ($r^2 = 0.88$). Data from across the northern hemisphere (Loewe, 1971) show a much weaker relationship ($r^2 = 0.69$); however both relationships are significant at the 99.9+% level. The addition to the global model of $\log_{10}$continentality improves the regression significantly ($r^2 = 0.81$).

The exploratory statistics suggest an additional hypothesis. Locally, the explanation of $\log_{10}$winter

TABLE II. MULTIPLE REGRESSION EXPLANATION OF WINTER PRECIPITATION AT GLACIAL EQUILIBRIUM LINE ALTITUDES

	r^2	n
Regional (data of Sutherland, 1984)		
Win ppt = 64.9 (sum. temp) + 76.9	0.88	9
$\log_{10}$ ppt = 0.156 (sum. temp) + 1.95	0.98	9
Global (data of Table I)		
Win ppt = 40.2 (sum. temp) + 80.2	0.69	25
$\log_{10}$ ppt = 0.155 (sum. temp) + 1.76	0.69	25
Win ppt = 42.0 (sum. temp) −72.7 ($\log_{10}$cont) + 231.6	0.81	25
Win ppt = 42.7 (sum. temp) −0.044 (cont) + 90.5	0.76	25
$\log_{10}$ ppt = 0.163 (sum. temp) −0.00016 (cont) + 1.80	0.75	25
$\log_{10}$ ppt = 0.157 (sum. temp) −0.112 ($\log_{10}$cont) + 1.99	0.70	25
Win ppt = f (sum. temp, $\log_{10}$cont, lat)	0.81	25
Win ppt = f (sum. temp, cont, lat)	0.76	25
$\log_{10}$ ppt = f (sum. temp, cont, lat)	0.75	25
$\log_{10}$ ppt = f (sum. temp, $\log_{10}$cont, lat)	0.70	25

All tested relationships are significant at $p > 99.9\%$.

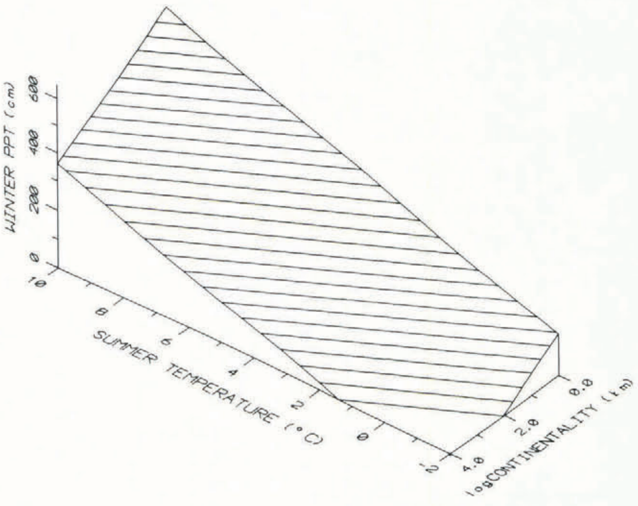

Fig. 1. Best-fit planar explanation of winter precipitation at glacial ELAs by summer temperature at the ELA and $\log_{10}$continentality ($r^2 = 0.81$). See text for approximate errors.

precipitation is much better than that of the untransformed precipitation data ($r^2 = 0.98$). However, across the northern hemisphere there is no improvement in predictive performance using $\log_{10}$winter precipitation as the dependent variable ($r^2 = 0.69$) and with the addition of continentality, explanation *decreases* using log-transformed winter precipitation data. The hypothesis of a non-linear relationship between summer temperature and winter precipitation requires further testing.

The replacement of temperature or continentality by latitude and cosine (latitude) to the analyses results in poorer explanation than the other variables. The addition of latitude to those variables results in negligible improvement in prediction and reduction in the statistical significance of the model (Table II).

Examination of residuals suggests some of the weaknesses of this analysis. The Gilman Glacier of northern Canada has very low precipitation for its temperature and continentality, but the nearly permanent pack ice gives it an effective continentality which is far greater. The Peyto and Place glaciers of western Canada have anomalous (opposite) winter precipitation for their geographic settings, which may indicate the effect of the prevailing winter storm track across southern British Columbia and Alberta. It is exactly such features which this technique is intended to identify, so such anomalies should be viewed as positive, rather than negative, features of this analysis.

DISCUSSION

Clearly, Loewe's (1971) suggestion of control of climatic conditions at the ELA by continentality is not rejected by this analysis. The *cause* of that control is not indicated by this analysis because of the lack of consistency in results of analyses involving transformed variables, although the energy inputs to maritime glaciers by condensation and longwave radiation from clouds and the sinks of evaporative and sublimation loss in continental regions are logical explanations (Paterson, 1969).

The conclusion of the significance of continentality is not exactly a test, because the original hypothesis was based on a major part of this data set. A better test would be to:

(a) collect data independent to those of Loewe (1971) and Sutherland (1984),

(b) ensure comparable months and years of record,

(c) attempt to get equal representation of maritime and continental glaciers to reduce one possible bias, and

(d) compare the results of multiple regression analysis of such data to those from this study.

IMPLICATION AND APPLICATION

The results of this study suggest that winter precipitation at glacial ELAs can be adequately estimated if summer temperature and continentality are known. "Adequately" here implies a 95% confidence interval within 100 cm H_2O year^{-1} for individual glaciers and within an average of 20 cm H_2O year^{-1} for a number of glaciers near the group centroid to within 150 cm H_2O year^{-1} for individual glaciers and within an average of 100 cm H_2O year^{-1} for a number of glaciers at the corners of Figure 1. This predictive ability can be tested against independent data, such as that for the Grasshopper Glacier of Montana, U.S.A. (Alford and Clark, 1968; Kasser, 1973). The predicted winter precipitation at the ELA of this continental (1500 km) glacier of 316 cm H_2O year^{-1} (range: 199 to 433) exceeds the reported precipitation of 160 cm H_2O year^{-1}. The two-year record may be too short for reliable estimation, or the numerical model presented here may overestimate precipitation in continental environments.

While this technique is valuable for the estimation of climates of some existing but largely inaccessible glaciers (cf. Khodakov, 1975), it may have its greatest utility in the reconstruction of paleoenvironments. Summer temperatures or average temperature depression have been estimated from general circulation models, pollen transfer functions, and other proxy data for large areas of the Earth's surface. Because continentality has been measured in the least restrictive sense (distance to nearest major water body), it can readily be estimated for former water bodies as well.

In a pilot application of this study, Locke (in press) has applied the mathematical model of winter accumulation as a function of summer temperature and $\log_{10}$continentality (Table II) to the problem of reconstruction of peak-glacial climates of the montane region of western Montana, U.S.A. A conservative assumed cooling of 10°C relative to present (Barry, 1983) yields maximum estimated winter precipitation across the region. The inferred approximate peak-glacial climate was drier than present, except in areas of exceptional moisture recharge from glacial lakes and of converging airflow around and off of the Laurentide and Cordilleran ice sheets. Although any individual estimate of precipitation is subject to an uncertainty of about 125 cm, the average difference should be less than 60 cm. Such estimates can be only as good as the assumptions on which they are based, both in the analysis and in the application, but they provide a quantitative approximation of past climates which is otherwise unavailable.

ACKNOWLEDGEMENTS

This paper profited from discussions with D.R. Murray and E.M. Leonard, the comments of two anonymous reviewers, and the encouragement of the editor, D.R. MacAyeal.

REFERENCES

Ahlmann, H.W. 1924. Le niveau de glaciation comme fonction de l'accumulation d'humidité sous forme solide. *Geogr. Ann.*, 6(3-4), 223-272.

Alford, D. and R. Clark. 1968. The 1967 mass balance of the Grasshopper Glacier, Montana. *Northwest Sci.*, **42**, 115-123.

Barry, R.G. 1983. Late-Pleistocene climatology. *In* Porter, S.C., *ed. Late Quaternary environments of the United States. V. 1: The Late Pleistocene.* Minneapolis, MN, University of Minnesota Press, 390-407.

Box, G.E.P. and D.R. Cox. 1964. An analysis of transformations. *J. R. Stat. Soc., B*, **26**, 211-252.

Box, G.E.P. and P.W. Tidwell. 1962. Transformation of the independent variables. *Technometrics*, **4**, 531-550.

Kasser, P. 1973. *Fluctuations of glaciers: 1965–1970.* Paris, International Association of Hydrological Sciences/ UNESCO.

Kerschner, H. 1985. Quantitative palaeoclimatic inferences from lateglacial snowline, timberline and rock glacier data, Tyrolean Alps, Austria. *Z. Gletscherkd. Glazialgeol.*, **21**, 363-369.

Khodakov, V.G. 1975. Glaciers as water resource indicators of the glacial areas of the USSR. *International Association of Hydrological Sciences Publication* 104 (*General Assembly of Moscow 1971 — Snow and Ice*), 22-29.

Locke, W.W. 1989. Present climate and glaciers of western Montana, U.S.A. *Arct. Alp. Res.*, **21**(3), 234-244.

Locke, W.W. In press. Late Pleistocene glaciers and climate of western Montana, U.S.A. *Arct. Alp. Res.*

Loewe, F. 1971. Considerations on the origin of the Quaternary ice sheet of North America. *Arct. Alp. Res.*, **3**(4), 331-344.

Mitchell, V. Unpublished. The regionalization of climate in montane areas. (Ph.D. thesis, University of Wisconsin, Madison, 1969.)

Paterson, W.S.B. 1969. *The physics of glaciers*. Oxford, etc., Pergamon Press.

Porter, S.C., K.L. Pierce, and T.D. Hamilton. 1983. Late Wisconsin mountain glaciation in the western United States. *In* Porter, S.C., *ed. Late Quaternary environments of the United States. V. 1: The Late Pleistocene.* Minneapolis, MN, University of Minnesota Press, 71-111.

Snedecor, C.W. and W.G. Cochran. 1980. *Statistical methods. Seventh edition.* Ames, IA, Iowa State Press.

Sutherland, D.G. 1984. Modern glacier characteristics as a basis for inferring former climates with particular reference to the Loch Lomond stadial. *Quat. Sci. Rev.*, **3**(4), 291-310.