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A STATISTICAL ANALYSIS OF SOME MEASURES OF THE STATE OF A GLACIER'S "HEALTH"

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ABSTRACT. Data from Norwegian glaciers and statistical tests are presented which suggest that vertical net-budget gradient, ablation gradient and equilibrium-line altitude can be taken as characteristic for any particular glacier. The usefulness of these conceptual models as predictive techniques for the regional determination of glacier net budget when only a small sample is available, and in palaeo-net-budget studies, is shown to be limited.

RÉSUMÉ. *Une analyse statistique de quelques mesures de l'"état de santé" d'un glacier.* Des tests statistiques sur des données provenant de glaciers Norvégiens suggèrent que des grandeurs comme le gradient vertical de variation du bilan ponctuel, le gradient d'ablation et l'altitude de la ligne d'équilibre peuvent être prises comme caractéristiques d'un glacier particulier. Mais la valeur de ces modèles théoriques comme techniques de prédiction pour la détermination à l'échelle régionale des bilans glaciaires s'avère limitée lorsque l'on dispose seulement d'un petit échantillonnage ainsi que dans les études des paléo-bilans.

ZUSAMMENFASSUNG. *Statistische Analyse einiger Messungen zum "Gesundheitszustand" eines Gletschers.* Es werden Daten von norwegischen Gletschern und statistische Untersuchungen vorgelegt, die nahelegen, dass der Vertikalgradient des Nettohaushaltes, der Ablationsgradient und die Höhe der Gleichgewichtslinie als charakteristisch für einen bestimmten Gletscher gelten könnnen. Die Brauchbarkeit dieser Konzeption als Mittel zur regionalen Vorhersage des Nettohaushaltes eines Gletschers bei Vorliegen nur beschränkter Beobachtungen und für Nettohaushaltsuntersuchungen in der Vergangenheit erweist sich als begrenzt.

INTRODUCTION

Several parameters have been used recently to give an estimate of the instantaneous state of "health" of glaciers. The vertical net-budget gradient at the equilibrium line has been used by both Shumskiy (1946) and Meier and Post (1962), and termed respectively the "energy of glacierization" and the "activity index". Indeed Meier and Post (1962) state: "This quantity reflects the growth or shrinkage in the mass of a glacier during a budget year. It is the single best indicator of a glacier's instantaneous state of 'health'". The ablation gradient has been used by both Haefeli (1962) and Schytt (1967). The former proposes "its use not only in mass-balance studies but also as one of the most important terms characterizing the influence of climate on glaciers". Schytt is of slightly different opinion: "An analysis of the 20 year long series of ablation measurements on Storglaciären, Sweden, shows that the ablation gradient varies considerably from one year to another, that the ablation gradient is dependent upon certain meteorological parameters, but that this relationship is complex".

Meier and Post (1962) were also responsible for the introduction of the concept of the equilibrium-line altitude (E.L.A.) and state: "The equilibrium line altitude, a useful parameter, is determined by the general climatological environment and the net budget for each particular year".

Although these conceptual models have been variously used in glaciological work, there has been no test of their statistical validity, particularly in terms of their possible use in glacial geology where techniques need to be based, where possible, on models derived from the study of present-day glaciers. To remedy this situation the data published for nine Norwegian glaciers, for the years 1964–68 inclusive, were the subject of statistical analysis, to evaluate the possibility of synchronous response of the glaciers to yearly climatic fluctuations. The nine glaciers for which sufficiently long records are available are:

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1. Folgefonni west
2. Folgefonni east
3. Hardangerjøkulen
4. Ålfotbreen
5. Nigardsbreen
6. Hellstugubreen
7. Gråsubreen
8. Blåisen
9. Storsteinfjellbreen

The locations are shown in Figure 1.

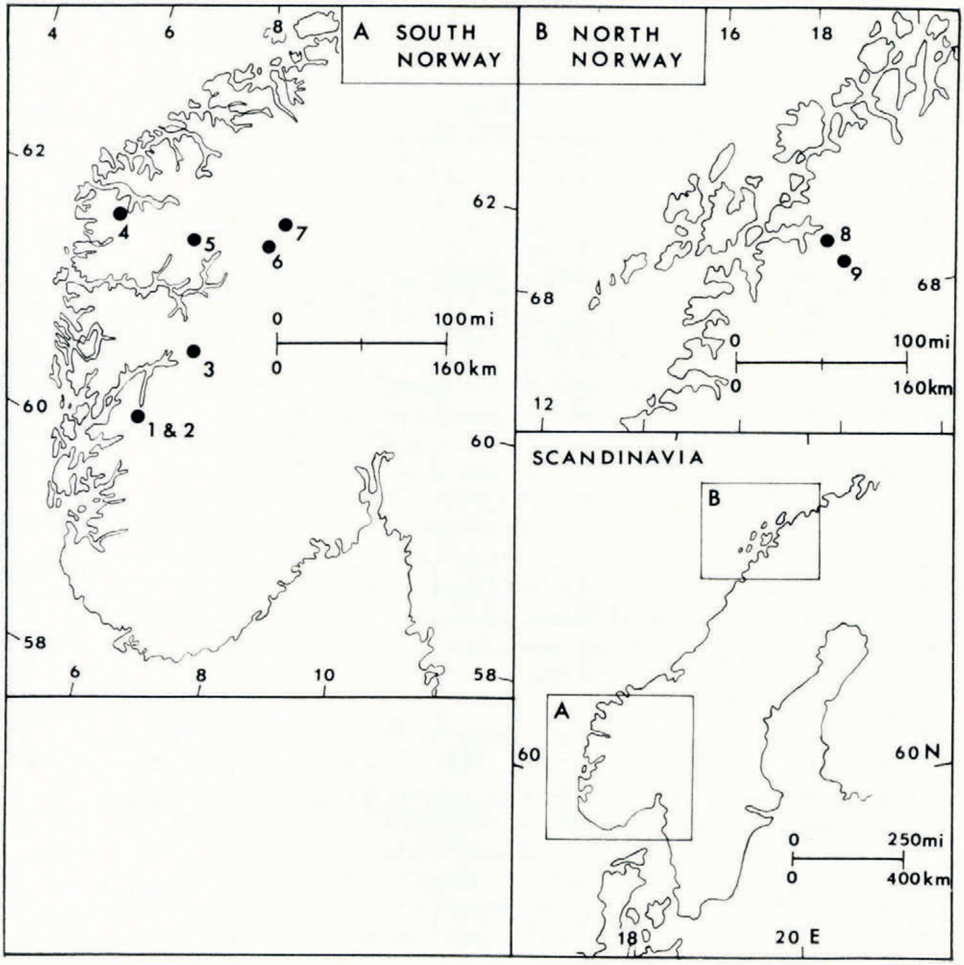

Fig. 1. Location of glaciers. 1 and 2 Folgefonni, 3 Hardangerjøkulen, 4 Ålfotbreen, 5 Nigardsbreen, 6 Hellstugubreen, 7 Gråsubreen, 8 Blåisen, 9 Storsteinfjellbreen.

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METHODS AND RESULTS

1. *Vertical net-budget gradient*

This parameter has been defined by Meier and Post (1962) as "the slope of the net budget curve at the equilibrium line". For the present analysis, the net-budget data for each glacier were plotted against elevation for the five-year period under consideration (Fig. 2). The gradient of the net budget curve at the equilibrium line (specific net budget equals zero) was determined after smoothing minor irregularities which, according to Meier and Post (1962), relate to the effect of topography and exposure on glacier net budgets. The resulting values are

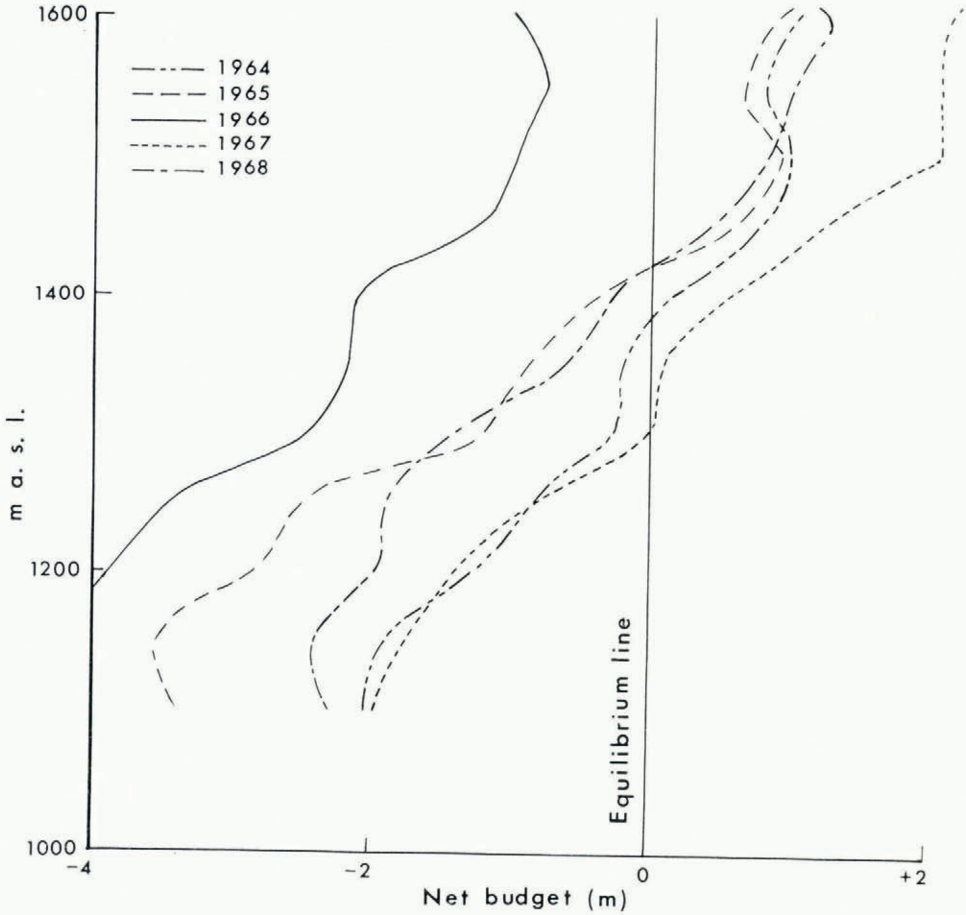

Fig. 2. Net budget against elevation for Folgefonni east, 1964–1969.

shown in Table I, omission indicating that no zero value for this specific net budget was achieved during that particular year. Figure 3A is a graph of all the values obtained against years.

To determine the validity of the hypothesis that vertical net-budget gradient can be considered characteristic of a particular glacier, a simple one-way analysis of variance was performed to determine if variance is significantly greater between, than within, individual glaciers, over the five year period. An F-ratio value of 5.4376 (significant at the 99% level) was obtained. The interpretation of these results is considered later.

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A more detailed analysis of the data was undertaken to establish the regional variability, and, therefore, the usefulness of vertical net-budget gradient as an indicator of glacier response to yearly climatic fluctuations. For this purpose values of Pearson's product moment correlation coefficient, r, were computed for all possible combinations of glaciers over the five-year period. The correlation matrix is shown in Table II.

TABLE I. VERTICAL NET-BUDGET GRADIENT cm/m

Glacier number	*1964*	*1965*	*1966*	*1967*	*1968*
1	0.765	0.975		1.14	1.24
2	0.94	1.365		1.61	2.03
3	0.855	1.0	0.805	1.08	1.27
4	1.23	0.655		0.845	1.59
5	0.91	0.788	0.695	0.895	0.96
6	0.55	0.925	0.74	0.925	0.78
7	0.52	0.595	0.395		0.436
8	1.03	0.40		0.895	0.88
9	0.88	0.8	0.55	0.6	0.625

TABLE II. CORRELATION MATRIX FOR VERTICAL NET-BUDGET GRADIENT

Glacier number	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1								
2	0.9823							
3	0.9637	0.9964						
4	0.2503	−0.4908	0.4501					
5	0.3449	0.4050	0.6903	0.8958				
6	0.6245	0.5200	0.4361	−0.5895	−0.1513			
7	−0.5832	−0.6308	−0.0100	−0.9863	0.1220	0.2830		
8	−0.0678	−0.0574	−0.0300	0.6480	0.8595	−0.6632	−0.7064	
9	−0.9451	−0.8809	−0.2374	−0.1786	0.2493	−0.4004	0.8436	−0.1264

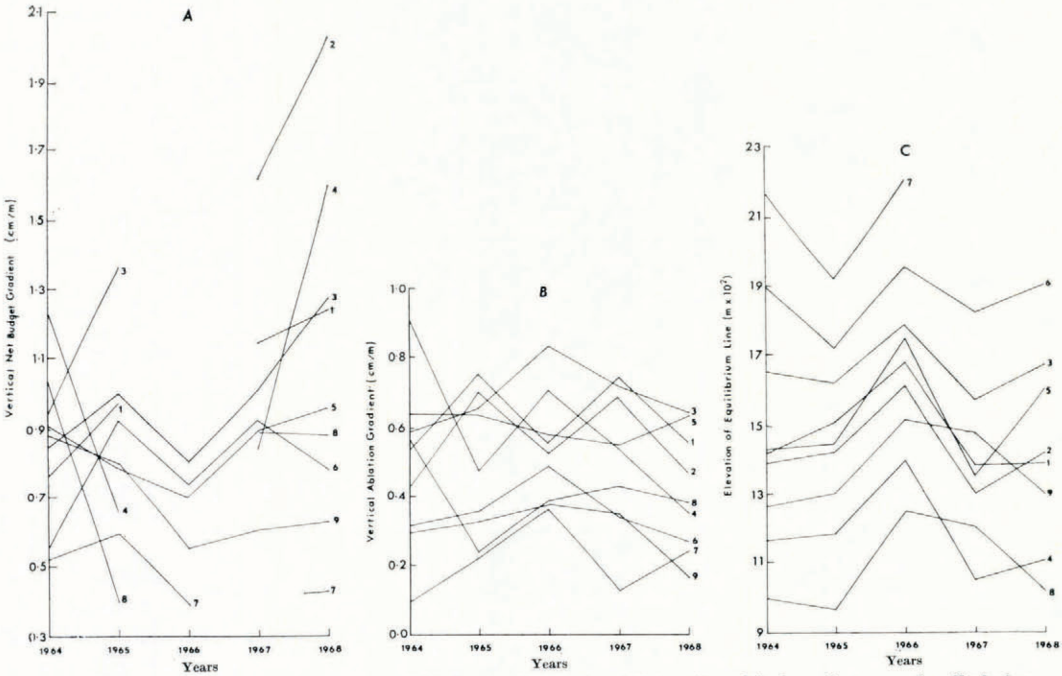

Fig. 3. Vertical net-budget gradient, vertical ablation gradient and equilibrium-line altitude against years for all glaciers.

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2. *Ablation gradient*

Schytt (1967) defines the ablation gradient as "the slope of a straight line drawn in such a way that it as closely as possible approximates the ablation curve". To satisfy these conditions a regression analysis was undertaken, of the form $y = a+bx$, where b is the gradient of the line. All analyses were significant at the 99% level with the exception of two, which were significant at the 95% level. The results are shown in Table III and Figure 3B.

TABLE III. ABLATION GRADIENT cm/m

Glacier number	*1964*	*1965*	*1966*	*1967*	*1968*
1	0.538	0.752	0.558	0.738	0.552
2	0.423	0.700	0.529	0.682	0.468
3	0.587	0.659	0.828	0.718	0.642
4	0.919	0.474	0.707	0.542	0.342
5	0.646	0.639	0.585	0.551	0.635
6	0.312	0.355	0.483	0.335	0.266
7	0.097	0.216	0.356	0.127	0.236
8	0.581	0.234	0.386	0.429	0.378
9	0.289	0.322	0.379	0.342	0.162

The values derived were subjected to the same statistical tests as were applied to the vertical net-budget gradients. The analysis of variance gave an F-ratio of 16.685 (significant at the 99% level). The results of the computations of r values are shown in Table IV.

TABLE IV. CORRELATION MATRIX FOR ABLATION GRADIENT

Glacier number	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1								
2	0.9708							
3	0.0625	0.2903						
4	−0.4022	−0.4296	−0.0412					
5	−0.3524	−0.4626	−0.7165	0.0574				
6	−0.0141	0.1884	0.8625	0.3312	−0.4277			
7	−0.2372	−0.0100	0.7474	−0.2539	−0.3128	0.6875		
8	−0.5801	−0.6752	−0.2964	0.7319	0.0000	−0.2014	−0.5211	
9	0.3717	0.4794	0.6273	0.4762	−0.5554	0.8137	0.1711	−0.0600

3. *Equilibrium-line altitude*

The equilibrium-line altitude was determined by simply reading the elevation of the zero net-budget point on the net-budget curves (Fig. 2). The results are shown in Table V and Figure 3C.

TABLE V. EQUILIBRIUM LINE ALTITUDE (m.a.s.l.)

Glacier number	*1964*	*1965*	*1966*	*1967*	*1968*
1	1 420	1 510	1 680	1 385	1 390
2	1 390	1 425	1 610	1 300	1 420
3	1 650	1 625	1 780	1 575	1 670
4	1 160	1 180	1 400	1 050	1 100
5	1 430	1 450	1 740	1 350	1 600
6	1 900	1 720	1 960	1 820	1 905
7	2 170	1 920	2 200		2 160
8	1 000	970	1 240	1 200	1 020
9	1 260	1 300	1 515	1 480	1 300

Again, the same statistical tests were applied. The analysis of variance gave an F-ratio of 32.536 (significant at the 99% level). The results of the computation of r are shown in Table VI.

Table VI. Correlation matrix for equilibrium-line altitude

Glacier number	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1								
2	0.9184							
3	0.8154	0.9659						
4	0.9713	0.4626	0.9040					
5	0.7284	0.9236	0.9539	0.7843				
6	0.2842	0.5184	0.7724	0.4551	0.6663			
7	0.0787	0.3574	0.6455	0.2807	0.5574	0.9896		
8	0.4467	0.3127	0.3453	0.3900	0.3243	0.4450	0.5785	
9	0.5043	0.3255	0.3059	0.4034	0.3077	0.2819	0.3674	0.9777

Discussion of results

1. *Analysis of variance*

F-ratios for the three parameters tested were all found to indicate that the between-glacier variance is significantly greater than the within-glacier variance at the 99% level. This leads to the conclusion that the vertical net-budget gradient, ablation gradient and equilibrium line altitude show internal consistency for any particular glacier, and supports Meier and Post's (1962) contention that "curves of net budget as a function of altitude are displaced from year to year but do not change greatly in character".

2. *Correlation analysis*

The statistical parameter *r* was calculated to determine the degree of synchronous response of the conceptual models to yearly climatic fluctuations. Statistically significant values of *r* were extracted from the correlation matrices and plotted as a topological diagram (Fig. 4). Values of *r* were plotted when they were found to be significant at the 90%, 95% and 99% levels. A high positive correlation coefficient suggests the glaciers were responding in phase, relative to each other, to the yearly climatic fluctuations. Conversely, high negative correlation coefficients suggest they were responding out of phase. The three parameters being tested show a varying degree of response between the nine glaciers over the five-year period. In the case of the vertical net-budget gradient, Figure 4A, glaciers 1, 2 and 3 show comparable response, glacier 8 shows a strong negative response compared with 1 and 2. The remaining glaciers, 4, 5, 6, 7 and 9, show very weak correlation with all other glaciers over the period of study.

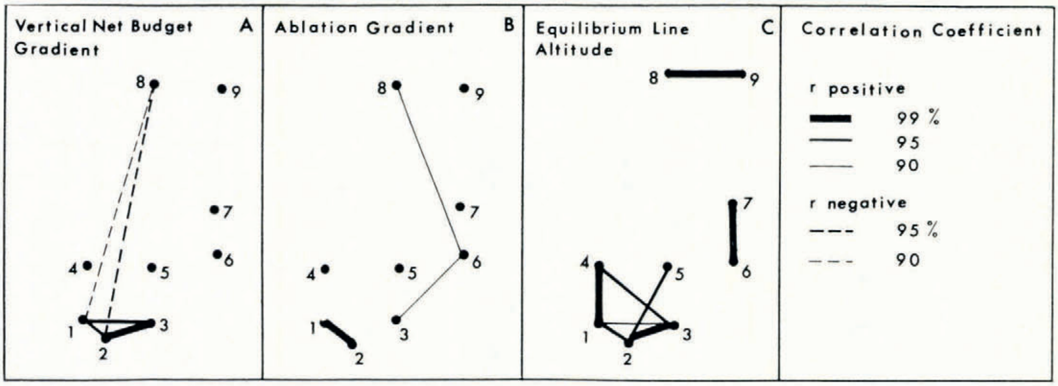

Fig. 4. Topological representation of r values, for all glaciers, for vertical net-budget gradient, ablation gradient and equilibrium-line altitude.

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Similarly, in the case of the ablation gradient (Fig. 4B) the *r* values derived were generally weak with the exception of glaciers 1 and 2. The most encouraging result is shown by the equilibrium-line altitude (Fig. 4C). Glaciers 1, 2, 3, 4 and 5 showed considerable agreement in their response to climatic fluctuations, but glaciers 8 and 9, and 6 and 7, although internally comparable, showed only weak *r* values when they were compared with other glaciers. The necessary conclusion from this analysis is in close agreement with the statement of Schytt (1967), that any relationship between these parameters and climate must be "complex".

Another conclusion is that all three conceptual models have a limited application as predictive techniques for glacier net budgets in a restricted area when only a small sample is available. The most useful parameter would appear to be the equilibrium-line altitude.

This conclusion also minimizes the applicability of these models to palaeo-net-budget—climatological prediction. Since there appears to be such a large amount of variability in existing glaciers, extrapolation into the past would seem to have no firm basis. However, it is interesting to note that in the case of vertical net-budget gradient all glaciers responded in the same direction to the largest fluctuation during the period of analysis, that is from the 1965/66 budget year. This suggests that the scale of climatic fluctuations has an important control on the degree of response of glaciers.

Conclusion

Data and statistical tests have been presented which suggest that the vertical net-budget gradient, vertical ablation gradient and equilibrium-line altitude can be taken as characteristic for any particular glacier. In terms of predictive techniques for response of glaciers to climatic fluctuations when only a small sample of glaciers is available, these parameters seem to have little applicability.

No account has been taken of the areal distribution of the glaciers with respect to either distance from the coast or latitude, which poses the question as to how small the areas for prediction can usefully be chosen. In this context glaciers 8 and 9 show little synchronous response with any other glaciers. It is hoped, however, that this paper will stimulate analysis of the relevant meteorological data to evaluate the variability of response of these parameters to climatic fluctuations.

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