Journal of Glaciology, Vol. 30, No. 106, 1984

SHORT NOTES

CAN THE MASS BALANCE OF A GLACIER BE ESTIMATED FROM ITS EQUILIBRIUM-LINE ALTITUDE?

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Abstract. The possibility of replacing or supplementing direct measurements of mass balance by estimates calculated from equilibrium-line altitude (ELA) measurements is investigated by statistical analyses of data from 31 glaciers. A linear relationship between mass balance and ELA in terms of two parameters, the effective balance gradient and the balanced-budget ELA, is tested. It is concluded that existing mass-balance series can be usefully extrapolated by using ELA data for additional years. However, accurate mass balance cannot be calculated for glaciers where no such measurements have been made because of the difficulties in prescribing the two model parameters with sufficient accuracy. For example, the effective balance gradient is of the order of 5 mm water/m so that errors of only a few decametres in the estimation of the balanced-budget ELA can have a great effect upon calculations of mass balance.

Résumé. *Le bilan de masse d'un glacier peut-il être estimé à partir de l'altitude de sa ligne d'équilibre?* La possibilité de remplacer ou de compléter les mesures directes de bilan de masse par des estimées calculées à partir des mesures de l'altitude de la ligne d'équilibre (ELA) est recherchée par analyse statistique des données fournies par 31 glaciers. Une relation linéaire entre le bilan de masse et l'ELA à deux paramètres: le gradient effectif du bilan et le bilan-budget ELA, est testée. On arrive à la conclusion que les séries de bilan de masse existantes peuvent être utilement extrapolées à l'aide des données d'ELA pour des années supplémentaires. Cependant des bilans de masse précis ne peuvent être calculés pour des glaciers où de telles mesures n'ont pas été effectuées, du fait de la difficulté dans le choix des deux paramètres du modèle avec une précision suffisante. Par exemple, le gradient effectif du bilan est de l'ordre de 5 mm d'eau par mètre, ce qui fait qu'une erreur de seulement quelques décamètres dans l'estimation de l'ELA peut avoir un effet important sur le calcul du bilan de masse.

Zusammenfassung. *Kann die Massenbilanz eines Gletschers aus der Höhe seiner Gleichgewichtslinie abgeschätzt werden?* Die Möglichkeit eines Ersatzes oder einer Ergänzung direkter Messungen der Massenbilanz durch Abschätzungen, die aus der Bestimmung der Hohe der Gleichgewichtslinie (ELA) hergeleitet sind, wird mit statistischen Analysen der Daten von 31 Gletschern untersucht. Eine lineare Beziehung zwischen der Massenbilanz und der ELA als Funktion zweier Parameter, nämlich des effektiven Bilanzgradienten und der ELA für einen ausgeglichenen Haushalt, wird geprüft. Es zeigt sich, dass vorhandene Massenbilanzreihen mit ELA-Daten für zusätzliche Jahre zutreffend extrapoliert werden können. Doch lassen sich exakte Massenbilanzen für Gletscher, an denen solche Messungen nicht vorgenommen wurden, infolge der Schwierigkeiten bei der ausreichend genauen Festsetzung der beiden Modellparameter nicht berechnen. So besitzt z.B. der effektive Bilanzgradient die Grössenordnung 5 mm Wasser pro Meter, so dass Fehler von nur wenigen Dekametern bei der Abschätzung der ELA für einen ausgeglichenen Haushalt sich stark auf die Massenbilanzberechnungen auswirken können.

INTRODUCTION

Glaciers exert a strong influence on stream-flow because they store and release water by means of irregular variations in their mass balance. This effect can be studied by direct measurement of mass balance in the field but this is laborious and expensive, especially in remote areas like Greenland. Is it possible to replace direct measurements of mass balance by indirect, and cheaper, methods?

Probably the most attractive possibility for indirect assessment of mass balance is to use the equilibrium-line altitude (ELA) as suggested by Meier and Roots (1982). In principle, the ELA can be determined directly in the field by measurements of a few stakes in the appropriate zone of the glacier while, by contrast, the determination of the total mass balance needs stakes scattered over the whole glacier. Alternatively, the ELA can be estimated from snow-line altitudes obtained by aerial reconnaissance (e.g. LaChapelle, 1962, or Meier and Post, 1962), or by satellite remote sensing as discussed by Østrem (1975).

The success of the above approach depends upon the existence of a definite relationship between glacier mass balance and ELA as suggested for individual glaciers by, for example, Liestøl (1967), Hoinkes (1970), and Østrem (1975). The general validity of such an equation, and the evaluation of its parameters, is the subject of the present paper. Technical problems associated with the determination of the ELA and snow-line altitude are outside the scope of this discussion although they may involve considerable practical difficulties, especially in areas like Greenland (Weidick and Thomsen, 1983).

BACKGROUND

A simple linear relation between the mean specific balance b_t and the equilibrium line altitude ELA_t for the same year, denoted by t, can be postulated as follows:

$$b_t = \alpha(ELA_0 - ELA_t) \qquad (1)$$

where ELA_0 is the balanced-budget ELA, i.e. the ELA when the mean specific balance is zero, and α will be termed the *effective* balance gradient as it represents a kind of time- and space-average of the balance gradient. The parameters α and ELA_0 are assumed to be constant for any particular glacier for the purposes of the present analysis, and are defined by the equation. However, it is likely that the true balance gradient will fluctuate from year to year, and from place to place on the glacier, while the balanced-budget ELA will show secular variations in connection with advance or retreat of the glacier.

If the specific balance on the glacier surface is a linear function of elevation, i.e. if the balance gradient is constant, the parameter ELA_0 will equal the mean elevation of the glacier E_{mn}, and α will be identical to the constant balance gradient. This was first pointed out by Kurowski (1891) and rediscovered by Liestøl (1967). With the extra assumption of a symmetrical distribution of glacier area with elevation, the term ELA_0 will also be equal to the median elevation of the glacier E_{50}. For this latter reason it is often suggested that glaciers should have a balanced budget with an accumulation area ratio (AAR) equal to about 0.5 (Meier and Post, 1962) and, accordingly, the median elevation parameter is recommended for inclusion in national glacier inventories (Müller and others, 1977). However, balanced-budget AAR values of about 0.67 seem to be more appropriate for alpine glaciers (Gross and others, [1977]) so that ELA_0 may be somewhat lower than the mean elevation for many glaciers. On the other hand, in areas of extremely high relief like the Andes or Himalaya, the balanced-budget AAR might be less than 0.5 due to avalanche-accumulation or topographic "concentration" of precipitation (Müller, 1980).

The ELA concept is not applicable to all glaciers. For example, on glaciers with a small elevation range, local variations in specific balance can mask the altitudinal variations so that there is no simple average elevation for a line separating the ablation area from the accumulation area. In an extreme case where the specific balance values are more or less randomly distributed over the glacier surface, the balanced-budget AAR will be about 0.5 and the ELA concept will be meaningless. In this case the effective balance gradient will be zero.

The above concepts are also difficult to apply to large ice masses like the ice tongues draining the Greenland ice sheet. Because of the problems in mapping such areas and, especially, in delineating the extent of the accumulation area, parameters like the median elevation E_{50} and accumulation area ratio AAR are difficult to assess. For the same reason, it is difficult to calculate mean specific balance for such ice bodies even when specific balances have been measured at many points. These problems are now under investigation by Grønlands Geologiske Undersøgelse but it is still too early to draw any firm conclusions.

From Equation (1) it seems that the main problem for calculating the mass balance from the ELA lies in the correct choice of the effective balance gradient α and balanced-budget ELA. This will be examined in the following section by analysis of data compiled from the literature.

METHOD AND RESULTS

The parameters in Equation (1) were evaluated by least-squares for a total of 31 glaciers, each of which has at least five years of record. The necessary data (including mass balance, ELA, and the area distribution with elevation) were mainly compiled from Kasser (1967, 1973) and Müller (1977). The data set is essentially the same as used in an earlier paper by Braithwaite and Müller (1980). The reader is referred to that paper for details of periods of records and sponsoring agencies. The sample of 31 glaciers is stratified into five geographical groups as follows;

Group I - Arctic North America: Baby Glacier (1), White Glacier (2), and Devon Island Ice Cap (3).

Group II - Western North America: Gulkana Glacier (4), Wolverine Glacier (5), Ram River Glacier (6), Peyto Glacier (7), Woolsey Glacier (8), Place Glacier (9), Sentinel Glacier (10), Blue Glacier (11), and South Cascade Glacier (12).

Group III - Scandinavia: Storglaciären (13), Trollbergdalsbreen (14), Engabreen (15), Høgtuvbreen (16), Ålfotbreen (17), Nigardsbreen (18), Gråsubreen (19), Hellstugubreen (20), Hardangerjøkulen (21), and Austre Memurubre (22).

Group IV - The Alps: Limmerngletscher (23), Silvrettagletscher (24), Hintereisferner (25), Vernagtferner (26), Griesgletscher (27), Kesselwandferner (28), Langtalferner (29), and Caréser (30).

Group V - Central Asia: Tsentralnyy Tuyuksu (31).

The included glaciers extend from lat. 43 to 79°N. but the sample is biased towards relatively small temperate glaciers. The sample also includes only the types of glacier for which the ELA is a well-defined concept. The geographical grouping is arbitrary and it is not postulated that the groups are homogeneous. Indeed, the second and third groups especially will contain glaciers from both maritime and continental environments.

In all cases, high negative correlations were found between the mean specific balance and the ELA series. The individual correlation coefficients ranged from -0.81 to -0.99, with a mean of -0.95 for the sample of 31 glaciers. Naturally, the correlations are affected by sampling, especially as some of the series are as short as only five years. However, in the present case, the high correlations for the longer series lend credence to the correlations for the short series.

Calculated values of effective balance gradient and balanced-budget ELA are given in Table I for the 31 glaciers divided into five groups. For convenience, the balanced-budget ELA values have been expressed as deviation from various orometric parameters; the mean elevation E_{mn}, the median elevation E_{50}, and the elevation E_{67} which corresponds to AAR = 0.67.

With the exception of the first group, the average balance gradients for the different groups are similar although there are large within-group variations, expressed by the standard deviations SD. Haefeli (1962) has suggested that "ablation gradient" (by which he clearly meant the balance gradient in the ablation area) should be a function of latitude. Accordingly, the 31 individual values are plotted against latitude in Figure 1 but, except for the low gradients for the three northernmost glaciers, there is no obvious trend with latitude. This is in agreement with Schytt (1967), who found no clear relation between ablation gradient (correctly defined) and latitude. One suspects that the contrast between maritime and continental environments within each group predominates over any possible latitudinal effect, e.g. glaciers with high mass exchanges often have high

TABLE I. MEAN AND STANDARD DEVIATION (SD) OF THE EFFECTIVE BALANCE GRADIENT α IN mm WATER/m TOGETHER WITH DEVIATIONS OF BALANCED-BUDGET ELA FROM VARIOUS OROMETRIC PARAMETERS IN METRES

Group	*Cases*	α		E_{mn} - ELA_0		E_{50} - ELA_0		E_{67} - ELA_0	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Arctic N. America	3	1.6	-	+120	-	+180	-	+50	-
Western N. America	9	5.4	± 1.4	+ 30	± 40	+ 30	± 50	-70	± 30
Scandinavia	10	6.3	± 1.9	+ 30	± 10	+ 30	± 30	-30	± 30
The Alps	8	5.6	± 2.3	+ 40	± 30	+ 70	± 40	-30	± 40
Central Asia	1	(5.2)		(+ 40)		(+ 30)		(-30)	
Combined	31	5.4	± 2.2	+ 40	± 40	+ 50	± 60	-30	± 50

ELA_0: Calculated balanced-budget ELA
E_{mn}: Mean elevation of glacier
E_{50}: Median elevation of glacier
E_{67}: Elevation above which 67% of glacier area lies

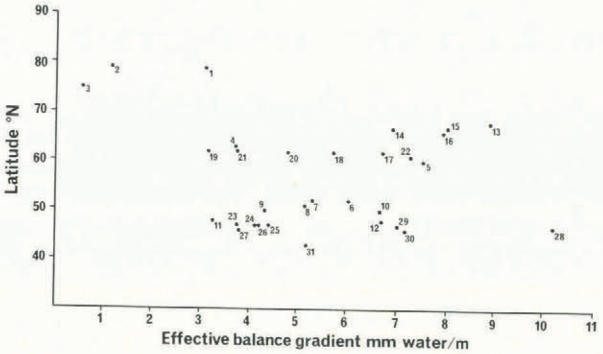

Fig. 1. Effective balance gradient α plotted against latitude for 31 glaciers. The numbering of the points corresponds to the glacier numbers given in the text.

gradient values also. At the same time, one might expect a sharp discontinuity between temperate and sub-polar glaciers but the latter are represented by three out of the 31 cases so that it is not possible to examine the question in any detail.

The results in Table I show that mean deviations of the balanced-budget ELA from the various orometric parameters are generally of the order of a few tens of metres (excluding the three northernmost glaciers). The balanced-budget ELA is generally lower than both the mean and median elevations, E_{mn} and E_{50}, while it is usually higher than E_{67}. Doubtless this reflects the fact that the specific balance on most glaciers has a lower gradient in the accumulation area than in the ablation area so that a proportionately larger accumulation area is required to produce a balanced budget. Once again, this effect may partly reflect contrasts between maritime and continental environments.

For the 31 glaciers the mean elevation range between E_{50} and E_{67} is 90 m (standard deviation ±50 m). This figure gives a good idea of the uncertainty in estimating balanced-budget ELA if one does not have any mass-balance data from the glacier.

CALCULATION OF MASS BALANCE FROM EQUILIBRIUM-LINE DATA

There are two practical cases that could arise. In the first case one might want to extend an existing mass-balance series by using ELA data for additional years, while in the second case one might want to calculate mass balance for glaciers where no measurements have been made.

The first case is the simpler. The appropriate values of effective balance gradient α and balanced-budget ELA can be calculated according to Equation (1) using the record available from the glacier. The mass balance for additional years can then be calculated from ELA data for as many other years as such data are available. Clark and Bruce (1967) give a formula for calculating the effective length of series which have been extrapolated by correlation methods. Assuming the correlation coefficient between mass balance and ELA to be about -0.95 (the average of the 31 cases studied here), their formula shows that a five-year mass-balance record can be extended to an effective length of 8.6 years by the use of an extra five-year record for the ELA. This might be attractive from the financial point of view if cheap, and reliable, methods of obtaining ELA data are available on an operational basis. On the other hand, if a few years of mass-balance data are available for a particular glacier, there will be other methods by which the series can be extrapolated, e.g. by correlation with a nearby long-term climate station as done by Liestøl (1967), Martin (1974), Hoinkes and Steinacker ([1975]), and Braithwaite (unpublished) among others. Such methods might be competitive with the presently described method using the ELA.

The second case, when one has no measured mass-balance data to calibrate the model, is more difficult. The problem is to guess the appropriate values of the effective balance gradient α and balanced-budget ELA to be applied to the "unknown" glacier. From Table I a value of about 5 mm water/m (in round figures) appears to be typical for α while the (unknown) balanced-budget ELA will lie somewhere between E_{50} and E_{67}, i.e. with an uncertainty range of the order of one hundred metres. The parameters E_{50} and E_{67} can be evaluated by planimetric measurements on a topographic map of the glacier if one is available. Naturally, maps of glaciers in remote areas can be rather inaccurate, but effects of map errors on the orometric parameters will be somewhat mitigated by the fact that the measured ELA data will be referred to the same map.

In order to illustrate the calculation of long-term mass balance of an unknown glacier, the above assumptions were applied to the 31 glacier series analysed in the previous section. The mean and standard deviation of the resulting errors for the 31 glaciers divided into five groups are shown in Table II for various assumptions represented by Models 0 to 3. Models 1 to 3 all assume an effective balance gradient of 5 mm water/m while Model 1 assumed the balanced-budget ELA to be given by E_{50}, Model 2 assumes it to be given by E_{67}, and Model 3 uses the correct balanced-budget ELA to illustrate the effects of errors in the effective balance gradient. Model 0 assumes that all mass balances are zero and is given

TABLE II. MEAN AND STANDARD DEVIATION (SD) OF ERRORS IN CALCULATING LONG-TERM BALANCES FOR 31 GLACIERS USING ELA DATA. UNITS ARE mm WATER

		Model 0		*Model 1*		*Model 2*		*Model 3*	
Group	*Cases*	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Arctic N. America	3	+ 50 ±	-	+730	-	+ 80	-	-250	-
Western N. America	9	+ 90 ±	300	+160 ±	205	-320 ±	140	+ 10 ±	90
Scandinavia	10	+ 80 ±	430	+135 ±	130	-170 ±	170	- 50 ±	150
The Alps	8	+120 ±	170	+330 ±	160	-130 ±	190	- 20 ±	60
Central Asia	1	(+ 70)		(+150)		(-150)		(0)	
Combined	31	+ 90 ±	290	+250 ±	260	-180 ±	206	- 44 ±	140

Model 0: Simply assumes zero balance for all cases
Model 1: Balanced-budget $ELA_0 = E_{50}$
Model 2: Balanced-budget $ELA_0 = E_{67}$
Model 3: Uses correct balanced-budget ELA_0
Models 1 to 3 all assume an effective balance gradient of 5 mm water/m

as a standard of comparison for the other models, i.e. as an analogy to the persistence forecast in meteorology.

Comparing the results of the Models 1 to 3 in Table II with Model 0 shows that some rather large errors can arise. For example, for the three northernmost glaciers none of the models give better results than simply assuming zero mass-balance. For all the other groups, mean errors can be reduced by choosing an orometric parameter intermediate between E_{50} and E_{67}. The standard deviation of the error involved in neglecting variations of effective balance gradient is of the order of ±60 to ±150 mm water/m (Model 3). By contrast, the error due to the combination of this effect with the uncertainty in balanced-budget ELA has a standard deviation of the order of ±130 to ±210 mm water (Models 1 and 2). For the "Western N. America" and "Scandinavia" groups, Models 1 and 2 will both reduce random errors compared to Model 0. Little reduction is achieved for glaciers in "The Alps" group because random errors in the models are of similar magnitude to the mass-balance variations between the glaciers within the group.

The above results are not especially encouraging. Random errors of the order of 100 to 200 mm water for the estimation of annual mass balances might be acceptable. However, the above results relate to errors in long-term mean mass balances, i.e. mean values for periods 5 to 29 years for the present data set. The major source of error is apparently due to uncertainty in the correct choice of balanced-budget ELA for the individual glaciers. Some method of improving the estimation in the case of an unknown glacier must be found.

CONCLUSIONS

There is generally a high correlation between mean specific balance and equilibrium-line altitude (ELA) which is expressed by a linear equation involving two parameters; the effective balance gradient and the balanced-budget ELA. However, these two parameters vary from glacier to glacier in a way which is difficult to predict accurately. This means that one can estimate accurate mass balances from the ELA after one has collected a few years of record to evaluate the parameters for the glacier in question. Existing mass-balance series can, therefore, be extrapolated by the use of ELA data. In the case of an unknown glacier, where no mass-balance measurements are available, one has to guess the appropriate values of the parameters, and the estimated mass balances are correspondingly less accurate. However, the results might still be useful in areas with large mass-balance variations, i.e. larger than the errors involved in the estimation procedure.

The answer to the question posed in the title of the present paper is therefore rather equivocal. If one is faced with the problem of assessing stream-flow conditions in areas with extensive glacier cover, one must start mass-balance measurements on several glaciers to provide background information. Analysis of the data may allow one to estimate values of the effective balance gradient and balanced-budget ELA parameters which can be applied to other, unmeasured, glaciers in the same area. Estimates of glacier mass balance from ELA data can supplement field measurements of mass balance but cannot replace them at present.

ACKNOWLEDGEMENTS

I am grateful to Statsgeolog Anker Weidick and to my colleagues Poul Clement and Henrik Højmark Thomsen for their comments.

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MS. received 19 September 1983 and in revised form 28 February 1984