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 direct assessment of mass balance is to use the 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 decameters in the estimation of the balanced-budget ELA can have a great effect upon calculations of mass balance.

BACKGROUND

A simple linear relation between the mean specific balance \( b_t \) and the equilibrium line altitude \( \text{ELA}_t \) for the same year, denoted by \( t \), can be postulated as follows:

\[
 b_t = a(\text{ELA}_0 - \text{ELA}_t)
\]

where \( \text{ELA}_0 \) is the balanced-budget ELA, i.e. the ELA when the mean specific balance is zero, and \( a \) will be termed the effective balance gradient as it represents a kind of time- and space-average of the balance gradient. The parameters \( a \) and \( \text{ELA}_0 \) 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 \( \text{ELA}_0 \) will equal the mean elevation of the glacier \( E_{gm} \), and \( a \) 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 \( \text{ELA}_0 \) will also be equal to the median elevation of the glacier \( E_g \). 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, 1973) so that \( \text{ELA}_0 \) 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 accumulation or topographic "concentration" of precipitation, it is still too early to draw any firm conclusions. 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.
Measurements have been made.

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

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.

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; 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 \( \alpha \) 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.

### Table II. Mean and Standard Deviation (SD) of Errors in Calculating Long-Term Balances for 31 Glaciers Using ELA Data. Units Are mm Water

<table>
<thead>
<tr>
<th>Group</th>
<th>Cases</th>
<th>Model 0</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Arctic N. America</td>
<td>3</td>
<td>50</td>
<td>± 250</td>
<td>730</td>
<td>± 250</td>
</tr>
<tr>
<td>Western N. America</td>
<td>9</td>
<td>+ 90</td>
<td>± 300</td>
<td>+160</td>
<td>± 205</td>
</tr>
<tr>
<td>Scandinavia</td>
<td>10</td>
<td>+80</td>
<td>± 430</td>
<td>+135</td>
<td>± 130</td>
</tr>
<tr>
<td>The Alps</td>
<td>8</td>
<td>+120</td>
<td>± 170</td>
<td>+330</td>
<td>± 160</td>
</tr>
<tr>
<td>Central Asia</td>
<td>1</td>
<td>(+70)</td>
<td>(±150)</td>
<td>(+150)</td>
<td>(±150)</td>
</tr>
<tr>
<td>Combined</td>
<td>31</td>
<td>+90</td>
<td>± 290</td>
<td>+250</td>
<td>± 260</td>
</tr>
</tbody>
</table>

Model 0: Simply assumes zero balance for all cases
Model 1: Balanced-budget ELA = \( \text{Eg} \)
Model 2: Balanced-budget ELA = \( \text{Eg} \)
Model 3: Uses correct balanced-budget ELA

Models 1 to 3 all assume an effective balance gradient of 5 mm water/m

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 \( \text{Eg} \). Model 2 assumes it to be given by \( \text{Eg} \), 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
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 gives 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 Eeg and Eeg. The standard deviation of the error involved in neglecting variations of effective balance gradient is of the order of ± 60 to ± 150 mm water (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, there are 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.

REFERENCES


