Climate at the equilibrium line of glaciers

Atsumu Ohmura,
Geographisches Institut, Eidgenössische Technische Hochschule, CH-8057 Zürich, Switzerland

Peter Kasser
im Rennweg 45, CH-8704 Herrliberg, Switzerland

Martin Funk
Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Eidgenössische Technische Hochschule, CH-8092 Zürich, Switzerland

Abstract. The relationships between temperature, precipitation and radiation on glacier equilibrium lines are investigated, using 70 glaciers for which the mass balance and meteorological observations have been carried out for sufficiently long periods. It is found that the characteristic climate at glacier equilibrium lines can be described using the summer 3 months' temperature in a free atmosphere, annual total precipitation, and the sum of global and long-wave net radiation. All of these are measured at or very near the equilibrium-line altitudes. Then, it is shown how the shift of the equilibrium line will occur as a result of a climatic change. Finally, the effect of the shift of the equilibrium line on the annual mean specific mass balance is analytically derived and compared with observations. The present results make it possible to identify the altitudes in climate models where glacierization should begin, and to evaluate the mass-balance changes as a result of possible future changes in the climate.

Introduction

Glacier equilibrium lines are very important because they represent the lowest boundary of the climatic glacierization. The climates which prevail at glacier equilibrium lines are considered to be just sufficient to maintain the existence of glaciers. A thorough knowledge of the climates at equilibrium lines is, therefore, essential for understanding the relationship between climatic changes and glacier variations. Investigations along these lines of thought were previously pursued by Ahlmann (1948) and Loewe (1971). In view of the recent improvement in information on the equilibrium line, availability of more climatic data and the new requirements for climate modelling, the authors decided to formulate this problem from a different viewpoint.

Glacier equilibrium lines also have other important meanings. First, the year-to-year variation of the equilibrium-line altitude (ELA) is a good indicator of the variation in the total annual mass balance of the glacier. Secondly, but closely related to the first point, the largest standard deviation of annual zonal mass balance (mass balance for a certain altitude zone) is usually observed at around the ELA. Thirdly, a substantial part of the glacier meltwater originates from near the ELA (Ohmura and others, 1986).

Present Distribution of the ELA

There are, at least, two approaches to understanding the climate at the ELA. One is to pursue the processes of accumulation and melt, where the latter can be vigorously investigated from the energy-balance principle. The other approach can be made from the viewpoint of scaling, whereby the relevant variables for the ELA are selected and the relationships between them and the annual accumulation or ablation are sought statistically. The present work is aimed at finding the relationship between the climate and the glacier equilibrium line, based on the second approach. The ELA values used in this work are all directly derived from the mass-balance measurements. The glaciers considered in this work are those in mid-latitudes and polar regions. The glaciers in the tropics behave differently and will be treated separately later.
west slope of Greenland, west Scandinavia, the Alps, central Asia and the Andes, respectively. Other glacio-
climatologically important lines are also plotted to assist
interpretation.

The ELA on the west slope of the Greenland ice sheet
(Fig. 1a) falls from about 1500 m a.s.l. at the southern
end to 700 m a.s.l. on the northern slope. Often, the
annual mean 0°C isotherm is used as the ELA (Källén
and others, 1979; Oerlemans and Van der Veen, 1984).
It should be noted that the 0°C annual mean surface
temperature barely touches the southern tip of Green-
land and does not even intercept the ice sheet. This fact
demonstrates how unrealistic it is to approximate the
ELA with the 0°C annual mean surface temperature. If,
for some reason, the 0°C annual mean surface temper-
ature is preferred to be related to the ELA, the summer
3 months (JJA) surface temperature comes closest to the
ELA on the west slope of Greenland. A local depression
of the ELA at around 77° N is due to greater precipit-
ation from the North Water, one of the major recurring
polynyas in the Northern Hemisphere (Ohmura, 1976).

The ELAs are presently best known in Nor-
way. The ELAs in Figure 1b are all calculated by
the long-term mass-balance measurements with well-
chosen stake networks. All ELAs are distributed
within the annual mean and summer temperature zero
lines, descending on an average from 1400 to 1600 m
in Folgefonna/Hardangerjoklen to 1100–1350 m in the
Storsteinfjellbreen/Blaisen area over 900 km. A much
steeper descent in the ELA is seen, however, from the
interior of the Scandinavian peninsula to the Atlantic
coast. In the latitudinal cross-section along 61°40′ N
from Memurubreene, through Jostendalsbreen to Alfot-
breen, the ELA descends from 2050 to 1150 m in just over 150 km. In the east–west cross-section of southern Scandinavia, annual precipitation decreases rapidly from over 2000 mm within the first 50 km and reaches a minimum of less than 500 mm at Jotunheimen. This is one of the regions in the world where the precipitation gradient from the coast to the interior shows its effect clearly on the ELAs.

In the Alps, the ELAs (Fig. 1c) tend to appear at about 700 m above the zero annual mean temperature. The ELAs climb slowly from the French Alps to the Swiss Alps, reaching more than 3200 m on the north side of the Pennine Alps, especially in the Mischabel Range. The ELAs descend in the region of the Adula Group which is open to the Mediterranean. In the Austrian Alps, the highest ELAs are observed in the Ötztal Alps.

The ELA decrease to the south on the southern slope of the Himalaya (Fig. 1d) is due to the effect of the summer monsoon, greater precipitation and lower summer temperature in comparison with the northern lee side. On the Tibetan Plateau, the ELA falls only slightly with increase in latitude. The meridional temperature gradient in the middle troposphere is the smallest over the Tibetan Plateau within the entire Northern Hemisphere. The sudden drop in the ELA in the Tien Shan and the Altay Mountains is mainly due to the increase in vapour flux transported from the Atlantic (Xiao, 1981).

In the Andes (Fig. 1e), the ELA increases from the Equator towards 25°S which is at the latitude equivalent to the Atacama Desert on the Chilean coast. The ELA descends sharply from 30° to 40°S by as much as 5000 m. This abrupt descent in the ELA is attributed to the prevailing westerlies south of 35°S, which carries moisture from the Pacific Ocean.

**SUITABLE VARIABLES FOR DESCRIBING THE ELA**

In view of the facts presented above, it is appropriate to use at least two variables, precipitation and temperature, which represent the effects of accumulation and ablation, respectively. As will be demonstrated later, radiation is also an important factor to be considered.

ELAs are known accurately on about 100 glaciers at present where the annual mass-balance measurements have been carried out for a sufficiently long period. After some trial and error, it was found that the mean temperature of the summer months, June, July and August (December, January and February for the Southern Hemisphere) in the free atmosphere at the equivalent altitude as the ELA and the annual total precipitation at the ELA are convenient variables to characterize the ELA. Air temperature of the free atmosphere has an advantage over the screen-level air temperature, because the former is more easily accessible both in Nature and in models. The free-atmospheric temperature is calculated on the basis of data from Scherhag (1969) and NCAR World Weather Disc Records—Upper Air (TD-9648) and U.S. Department of Commerce (1982).
The radiation data, which are best suited for characterizing the glacier ELA, must be net radiation. As shown in Table 1, this is the prime energy source for the melt. It is, however, preferable to use global radiation plus long-wave net radiation to parameterize the ELA instead of net radiation, because the observation of net radiation on an ELA for the entire melt period is extremely rare and is liable to be influenced by local conditions, such as the albedo below the net radiometer. In addition, there is another advantage in avoiding the involvement of the albedo, because the parameterization of the ELA can be more conveniently formulated by using the glacier's external factors as independent variables and the albedo should be considered as the glacier's internal characteristics, which should be found as a solution. The radiative fluxes, as well as other climatological elements which are used in this work, are summarized in Table 2.

CLIMATIC CHARACTERISTICS OF THE EQUILIBRIUM LINE

The information on the mean equilibrium-line altitude, winter mass balance, summer precipitation, the free-atmospheric summer temperature, global radiation, global radiation plus long-wave net radiation is given in Table 3. The ELAs in this table are evaluated by mass-balance measurements with stakes. The distribution of the ELAs of these 70 glaciers in the precipitation-temperature (P-T) diagram is presented in Figure 2. In general, it can be interpreted that, if the P-T condition of a site falls in the sector within the zone of the points, such a location has a good chance of being on the ELA. If the site is not presently glacierized, it is very close to being glacierized with a slight increase in precipitation or decrease in summer temperature. If the P-T condition falls above the zone of the dots, the site is either in the ablation area or unglacierized. It is assumed that there exists a function of P and T at the ELA, \( f(P, T) = 0 \), which satisfies the condition for creat-
Table 2. Radiative components on or near the glacier equilibrium line

<table>
<thead>
<tr>
<th>Glacier</th>
<th>Global radiation (W m(^{-2}) (kly/3 mon.))</th>
<th>Long-wave net radiation (W m(^{-2}) (kly/3 mon.))</th>
<th>Sum of global and long-wave net radiation (W m(^{-2}) (kly/3 mon.))</th>
<th>Sources</th>
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<tr>
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<td>207 (39)</td>
<td>192 (36)</td>
<td>170 (32)</td>
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</tr>
<tr>
<td>White Glacier</td>
<td>239 (45)</td>
<td>212 (40)</td>
<td>207 (39)</td>
<td>(3), (4), (5)</td>
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<tr>
<td>Laika Glacier</td>
<td>227 (43)</td>
<td>210 (39)</td>
<td>201 (38)</td>
<td>(6)</td>
</tr>
<tr>
<td>Devon Ice Cap</td>
<td>270 (51)</td>
<td>201 (38)</td>
<td>192 (36)</td>
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<td>EGIG IV, Greenland Ice Shelf</td>
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<td>170 (32)</td>
<td>207 (40)</td>
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<td>207 (39)</td>
<td>(1), (11)</td>
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<td>Peyto Glacier</td>
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<td>207 (39)</td>
<td>201 (38)</td>
<td>(12)</td>
</tr>
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<td>Place Glacier</td>
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<td>Rhonegletscher</td>
<td>292 (55)</td>
<td>239 (45)</td>
<td>239 (45)</td>
<td>(20)</td>
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<td>No. 1 Glacier</td>
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<td>208 (38)</td>
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<td>218 (41)</td>
<td>218 (41)</td>
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Source references
(1) Canada. Department of Transport Meteorological Branch (1970); (2) Sagar (1962); (3) Andrews (1964); (4) Havens (1964); (5) Ohmura (1981); (6) Ohmura (1977); (7) Holmgren (1971); (8) Ambach (1963); (9) Ambach (1977); (10) Marshunova and Chernigovskiy (1971); (11) Young and Stanley (1976a); (12) Young and Stanley (1976b); (13) Mokievsky-Zubok and Stanley (1976b); (14) Mokievsky-Zubok and Stanley (1976a); (15) Ambach (1955); (16) Moser and others (1986); (17) Escher-Vetter (1985); (18) Palz and others (1979); (19) Wagner (1979); (20) Funk (1985); (21) Bai and Xie (1965); (22) Bai and others (1985); (23) Ohmura (1990); (24) Schwerdtfeger (1984); (25) Japanese Antarctic Research Expedition (1985).

The best-fit polynomial regression curve for the 70 glaciers under consideration is \( P = a + bT + cT^2 \), whereby \( a = 645 \), \( b = 296 \) and \( c = 9 \), and \( P \) and \( T \) are in mm w.e. and °C, respectively. The standard error of estimate is 200 mm w.e. Although the scatter of the points around the regression line is relatively narrow, it can be explained as being largely due to the different radiation condition. Global radiation alone does not explain the discrepancy amongst the dots, however, because of the often-observed negative correlation between global and net radiation for the ELA region (Ambach, 1974). The inclusion of long-wave radiation data makes it possible to understand the scatter. This result offers a possibility for parameterizing the ELA for climate models.

It is currently possible to estimate global radiation and long-wave net radiation on equilibrium lines for only 15 glaciers. The reason for the difficulty in calculating this component for other glaciers is the lack of observations on long-wave radiation. The general trend of each glacier around the regression line in Figure 2 is that for a given annual precipitation the glacier equilibrium lines under the lower summer temperature are found for glaciers with greater amounts of radiation, and vice versa. It appears that a temperature difference of 1°C is roughly equivalent to a 7 W m\(^{-2}\) (1.3 kly/3 months) radiation difference and 350 mm w.e. annual precipitation.

### RELATIONSHIP BETWEEN PRECIPITATION AND ACCUMULATION

Although accumulation originates primarily from precipitation, it is quantitatively different. It is, however, necessary to clarify the differences between these quantities. Of the 70 glaciers listed in Table 3, 12 glaciers are identified as suitable for a comparison of the annual precipitation and the combined amount of the winter balance and summer precipitation (Table 4). For some glaciers, the annual precipitation was measured at the mean ELA,
### Table 3

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<th>Water melt index (mm w.e.)</th>
<th>Ice retreat (mm w.e.)</th>
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<th>Source of publication</th>
<th>Responsible organisation</th>
<th>Year of institution</th>
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<th>Elevation range (m)</th>
<th>glacier volume (km³)</th>
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### Greenland

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### Notes

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**Note:** The table above is a representation of the document content, formatted into a readable and structured layout. It includes details of various glaciers, their coordinates, elevation, and other relevant data. The references and notes section provide additional context and sources for the data presented.
such as Rhonegletscher and Griesgletscher. For other glaciers, such as Laika Glacier and Law Dome, meteorological stations were located very near (within 300 m altitude) the ELA. For glaciers of the other group, such as White Glacier and No. 1 Urumqi glacier, the meteorological stations were closely located but with a much larger altitude difference. In these regions, however, the altitudinal dependency of precipitation is well established, so that it was possible to correct the annual total meteorological precipitation to the ELA. On all these glaciers, the summer precipitation and the winter glacier mass balance were measured at altitudes very close to the ELA or right on the long-term ELA (White Glacier, Rhonegletscher and No. 1 Urumqi glacier).

The comparison between the annual precipitation and the combined winter balance and summer precipitation

<table>
<thead>
<tr>
<th>Glacier</th>
<th>Coordinates</th>
<th>ELA (m a.s.l)</th>
<th>Winter mass balance (mm a.s.l)</th>
<th>Snow + summer precipitation (mm a.s.l)</th>
<th>Year of measurement</th>
<th>Responsible organization for mass balance</th>
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<tr>
<td>55 Vernagtferner</td>
<td>46°35'N, 10°40'E</td>
<td>3085</td>
<td>1000</td>
<td>1500</td>
<td>64-85 (25)</td>
<td>KGBAV</td>
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<td>2100</td>
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<td>1050</td>
<td>1250</td>
<td>64-66 (5)</td>
<td>IGUP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61 Dismant</td>
<td>43°19'N, 4°44'E</td>
<td>2310</td>
<td>2250</td>
<td>2500</td>
<td>65-78 (26)</td>
<td>GFM3SU</td>
<td></td>
</tr>
<tr>
<td>62 Tuxton</td>
<td>43°00'N, 77°00'E</td>
<td>3855</td>
<td>1000</td>
<td>1400</td>
<td>64-80 (5), (10), (23)</td>
<td>GS, ANKERR</td>
<td></td>
</tr>
<tr>
<td>63 No. 1 Glacier</td>
<td>43°07'N, 4°49'E</td>
<td>4650</td>
<td>550</td>
<td>400</td>
<td>59-74 (10)</td>
<td>LIGG, AS</td>
<td></td>
</tr>
<tr>
<td>64 Eiger Glacier</td>
<td>47°56'N, 8°46'E</td>
<td>3270</td>
<td>50</td>
<td>1000</td>
<td>64-66 (5)</td>
<td>IGUP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65 Rika Sanxia</td>
<td>29°00'N, 43°50'E</td>
<td>5650</td>
<td>20</td>
<td>700</td>
<td>74 (30)</td>
<td>WRI, UN</td>
<td></td>
</tr>
<tr>
<td>66 Gypsy Glacier</td>
<td>27°54'N, 8°31'E</td>
<td>5370</td>
<td>50</td>
<td>900</td>
<td>76 (31)</td>
<td>WRI, UN</td>
<td></td>
</tr>
<tr>
<td>67 No. 1 Glacier</td>
<td>47°56'N, 8°46'E</td>
<td>5270</td>
<td>10</td>
<td>1500</td>
<td>64-66 (5)</td>
<td>WRI, UN</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>68 Tameran Glacier</td>
<td>43°30'N, 17°02'E</td>
<td>1500</td>
<td>2500</td>
<td>3200</td>
<td>66-71 (5)</td>
<td>GS, MIV</td>
<td></td>
</tr>
<tr>
<td>69 Glaciers, Deception Island</td>
<td>63°00'N, 67°40'W</td>
<td>323</td>
<td>600</td>
<td>780</td>
<td>68-71 (5)</td>
<td>WRI, UN</td>
<td></td>
</tr>
<tr>
<td>70 Law Dome</td>
<td>66°00'S, 11°46'E</td>
<td>150</td>
<td>350</td>
<td>360</td>
<td>51-60 (32)</td>
<td>UA</td>
<td></td>
</tr>
</tbody>
</table>

**Sources of mass-balance data**

- (1) Hasteen-Smith and Senon (1970); (2) Konner (1979); (3) Sager (1964); (4) Arndt (1958); (5) Kaiser (1975); (6) Nisen (1984); (7) Aksel (1977); (8) Kran (1983); (9) Konner (1980); (10) Muller (1977); (11) Maksylov-Zubok and others (1985); (12) Selys (1955); (13) Senon (1995); (14) Tomson (personal communication); (15) Olsen (1986); (16) Wredick and Thomas (1986); (17) Braithwaite (personal communication); (18) Bjorn (personal communication); (19) Dowdowdell (personal communication); (20) Meyer and others (1971); (21) Tangborn and others (1977); (22) Marcus (1964); (23) Halbert (1985); (24) Maksylov-Zubok (1985); (25) Meyer and others (1988); (26) Maksylov-Zubok (1979); (27) Kuhn (1981); (28) Funk (1985); (29) Funk and Adler (unpublished); (30) Fujii and others (1976); (31) Agata and Sinow (1978); (32) Yasuoka and Isobe (1978); (33) Timmis (1986); (34) Xie (1986).

**Sources of radiation data**

so some glaciers, however, the winter mass balance is clearly balance plus summer precipitation. This is partly due and the accumulation through snow drift may be an important accumulation mechanism for such glaciers (Laika partic ularly of solid precipitation (Sevruk, 1983)). For some glaciers, however, the winter mass balance is clearly larger than the meteorologically measured precipitation, and the accumulation through snow drift may be an important accumulation mechanism for such glaciers (Laika Glacier, Woolsey Glacier, Hintereisferrner and Tsentral-nyy Tuyukus). The most important conclusion of this comparison is that the winter mass balance (accumulation) comes very close to the meteorological precipitation on a number of glaciers. This point justifies the approximation of the annual precipitation using the winter balance and the summer precipitation.

CLIMATIC CHANGE AND THE ELA SHIFT

The sensitivity of the ELA with respect to the change in climatic elements is examined. The shift of the ELA was investigated by Kuhn (1981) from the energy-balance viewpoint. In the present work, the statistical trend in the relationship developed in the previous section is used.
Table 4. Comparison of precipitation and accumulation on glaciers (mm w.e.) on ELA

<table>
<thead>
<tr>
<th>Glaciers</th>
<th>Annual total meteorological precipitation</th>
<th>Years of observation</th>
<th>Source of meteorological data</th>
<th>Glaciological winter balance plus meteorological summer precipitation</th>
<th>Years of observations</th>
<th>Source of glaciological data</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Glacier</td>
<td>300</td>
<td>1969–72</td>
<td>(1)</td>
<td>310</td>
<td>1969–72</td>
<td>(17)</td>
</tr>
<tr>
<td>Laika Glacier</td>
<td>340</td>
<td>1972–74</td>
<td>(2)</td>
<td>590</td>
<td>1972–74</td>
<td>(18)</td>
</tr>
<tr>
<td>Qamanarsup sermia</td>
<td>720</td>
<td>1980–84</td>
<td>(3),(4),(5)</td>
<td>990</td>
<td>1980–84</td>
<td>(3),(4),(5)</td>
</tr>
<tr>
<td>Woolsey Glacier</td>
<td>2500</td>
<td>1951–80</td>
<td>(6)</td>
<td>3100</td>
<td>1965–74</td>
<td>(11),(19)</td>
</tr>
<tr>
<td>Hintereisferner</td>
<td>1500</td>
<td>1957–59, 1974–78</td>
<td>(7),(8),(9)</td>
<td>2100</td>
<td>1957–59</td>
<td>(7)</td>
</tr>
<tr>
<td>Rhonegletscher</td>
<td>2400</td>
<td>1918–22</td>
<td>(10)</td>
<td>2250</td>
<td>1979–82</td>
<td>(20)</td>
</tr>
<tr>
<td>Tsentralnyy Tuyuksu</td>
<td>960</td>
<td>1959–70</td>
<td>(11)</td>
<td>1390</td>
<td>1964–70</td>
<td>(11)</td>
</tr>
<tr>
<td>No. 1 Glacier Urumqi</td>
<td>650</td>
<td>1958–78</td>
<td>(12)</td>
<td>570</td>
<td>1959–66</td>
<td>(21)</td>
</tr>
<tr>
<td>Hodges Glacier</td>
<td>1450</td>
<td>1951–60</td>
<td>(13)</td>
<td>1850</td>
<td>1957–58</td>
<td>(22)</td>
</tr>
<tr>
<td>Glacier, Deception Island</td>
<td>560</td>
<td>1944–67</td>
<td>(14)</td>
<td>780</td>
<td>1968–71</td>
<td>–</td>
</tr>
<tr>
<td>Law Dome</td>
<td>280</td>
<td>1958–60</td>
<td>(15)</td>
<td>320</td>
<td>Not specified</td>
<td>(23)</td>
</tr>
<tr>
<td>Griesgletscher</td>
<td>1710</td>
<td>1964–85</td>
<td>(16)</td>
<td>1800</td>
<td>1964–85</td>
<td>(16)</td>
</tr>
</tbody>
</table>

Source references
(1) Ohmura (1980); (2) Ohmura (1976); (3) Braithwaite (1987); (4) Braithwaite (1989); (5) Braithwaite (personal communication); (6) Atmospheric Environment Service (1982); (7) Hoinkes and Lang (1962); (8) Kuhn (1981); (9) Kuhn and others (1982); (10) Schweiz Bundesamt für Hydrologie (unpublished); (11) Kasser (1973); (12) Yang and others (1988); (13) WMO (1971); (14) British Meteorological Office (1978); (15) Schwerdtfeger (1984); (16) Funk and Aellen (unpublished); (17) Weiss (1984); (18) Blatter and Kappenberger (1988); (19) Müller (1977); (20) Funk (1985); (21) Zhang (1981); (22) Timmis (1986); (23) Xie (1984).

For the sake of simplicity, only the variation of temperature and precipitation is considered.

In Figure 3a, annual precipitation $P$ and summer temperature in a free atmosphere $T$ at the original ELA denoted by $z_0$ are indicated as solid lines which represent the present climate. The change in the climate for the altitude $z_0$ is represented by $\Delta P$ and $\Delta T$. As the result of the climatic change, the position of the ELA is shifted to $z_0 + \Delta z_0$ where the new precipitation and temperature are approximated by $P + \Delta P + \partial P/\partial z \Delta z_0$ and $T + \Delta T + \partial T/\partial z \Delta z_0$, respectively. The new precipitation and temperature should be on the solid line of the ELA in Figure 3b. The linear approximation of the new location of the ELA in the $P$–$T$ diagram is presented in Figure 3b. The relationship between the new temperature and precipitation should be

$$\Delta P + \frac{\partial P}{\partial z} \Delta z_0 = \left( \frac{\partial P}{\partial T} \right)_{z_0} \left\{ \Delta T + \frac{\partial T}{\partial z} \Delta z_0 \right\}$$  \hspace{1cm} (1)

where $(\partial P/\partial T)_{z_0}$ is the gradient of the function $f(P, T) = 0$ in Figure 2, and $(\partial P/\partial T)_{z_0} = b + 2cT$. Rearranging Equation (1) for $\Delta z_0$

$$\Delta z_0 = \frac{\Delta T - \left( \frac{\partial P}{\partial T} \right)_{z_0} \left( \partial T \right)_{z_0}}{\frac{\partial P}{\partial z} \left( \frac{\partial P}{\partial T} \right)_{z_0} - \frac{\partial T}{\partial z}}.$$  \hspace{1cm} (2)

Equation (2) represents several important features of the climate/glacier relationship. The vertical shift of the ELA is linear with the change in temperature. The ELA shift is also linear with the decrease in precipitation, although the effectivness of the precipitation change is not so large because $(\partial P/\partial T)_{z_0} = -2.5$ to $-3.3 \times 10^{-3}\, \text{K}\, \text{mm}^{-1}$. This statement is justified, as $\partial P/\partial T$, $\partial P/\partial z$ and $\partial T/\partial z$ are almost constant and therefore independent of changes in temperature and precipitation. This means that a change in precipitation of 300–400 mm w.e. corresponds to only 1°C temperature change.
For the same change of temperature and precipitation, the glaciers in a region of large lapse rate \( \Gamma = -\partial T/\partial z \) react less sensitively in comparison to those of small lapse rate. Since the regions of larger lapse rate are associated with a continental climate, the glaciers in arid environments must behave insensitively towards climatic changes, and vice versa.

**ELA AND MASS-BALANCE SENSITIVITY**

Each glacier possesses a different mass-balance sensitivity with respect to the shift of the ELA. The relationship between the annual mass balance and the ELA makes it possible to translate the shift of the ELA into the change in mass balance and holds important information concerning the effect of climatic changes on the glacierization. The ELA sensitivity of the mass balance is defined as the partial differential of mean annual specific balance by the ELA, \( \partial b/\partial \text{ELA} \) and calculated as the gradient of the \( b-\text{ELA} \) diagram. The mass-balance sensitivity of the ELA shift is calculated for 36 glaciers, for which long-term records of the mass balance and good topographic maps are available. Considering that the sensitivity can be parameterized by the annual specific turnover of the mass \( T \) and the surface gradient \( \alpha \) of the glacier, Figure 4 is made by taking \( \tau/\alpha \) as an independent variable, whereby \( \tau = (\bar{c} + |\bar{a}|)/2 \), \( \bar{c} \) and \( \bar{a} \) being the mean specific accumulation and ablation, respectively.

The explanation as to how the parameter \( \tau/\alpha \) is suited for expressing the mass-balance sensitivity \( \partial b/\partial \text{ELA} \) is given below. We consider a simplified two-dimensional glacier of a unit length (projected on the horizontal surface), with a constant surface gradient \( \alpha \) and density, extending from the origin of the coordinate system as illustrated in Figure 5. The surface change which is expected due to the mass balance of one budget year is also expressed by a linear equation \( z = \beta x - \gamma \). If more complicated expressions for the surface altitude and the mass balance are desired, non-linear curves can be used. The \( x \) and \( z \) coordinates of the equilibrium line are found to be \( (\gamma/(\beta - \alpha), \alpha \gamma/(\beta - \alpha)) \). The \( z \)-coordinate difference between the two lines is what we define as the annual mass balance in ice equivalent, therefore

\[
B = (\beta - \alpha)x - \gamma.
\]

Then, the mass-balance gradient of this glacier is

\[
\frac{\partial b}{\partial x} = \frac{\partial b}{\partial x} \frac{\partial x}{\partial z} = \frac{\beta - \alpha}{\alpha}.
\]

The total mass balance can be expressed as

\[
B = \int_0^1 b \, dx = (\beta - \alpha) \int_0^1 x \, dx - \gamma \int_0^1 dx.
\]

Consequently,

\[
B = \frac{\beta - \alpha}{2} - \gamma = \bar{b}.
\]

Equation (6) is justified, because the glacier has a unit
length. The glacier in steady state has $B = 0$, therefore
\[ \gamma = \frac{\beta - \alpha}{2}. \]  
\[ (7) \]

Then, the mass-balance sensitivity is
\[ \frac{\partial b}{\partial \text{ELA}} = \frac{\partial b}{\partial z_0} = \frac{\partial b}{\partial \gamma} \frac{\partial \gamma}{\partial z_0} = \frac{\alpha - \beta}{\alpha} \]  
\[ (8) \]

where $z_0$ is the altitude of the equilibrium-line ELA. Therefore,
\[ \frac{\partial b}{\partial \text{ELA}} = \frac{\partial b}{\partial z}. \]  
\[ (9) \]

Insofar as the linear approximation of the glacier surface and the mass balance are concerned, the mass-balance sensitivity becomes the same quantity as the negative of the mass-balance gradient.

However, since the mass-balance gradient is in reality variable depending on the altitude, it is desirable to replace it with a more stable quantity which characterizes the entire glacier. We use the concept of the annual specific mass turn-over of a glacier $\tau$, defined earlier, which is the mean rate of mass inflow or outflow with respect to the unit surface area of the glacier.

For the glacier under consideration:
\[ \tau = \frac{1}{2} \left\{ \int_{0}^{1} \gamma/(\beta - \alpha) \left[ \gamma - (\beta - \alpha)x \right] dx 
+ \int_{0}^{1} [(\beta - \alpha)x - \gamma] dx \right\} 
= \frac{1}{2} \left( \frac{\gamma^2}{\beta - \alpha} + \frac{\beta - \alpha}{2} - \gamma \right). \]  
\[ (10) \]

For glaciers with near steady state, that is Equation (7) holds, and
\[ \tau \approx \frac{\beta - \alpha}{8} \quad \text{or} \quad \beta - \alpha \approx 8\tau. \]  
\[ (11) \]

Therefore,
\[ \frac{\partial b}{\partial \text{ELA}} = -8 \frac{\tau}{\alpha}. \]  
\[ (12) \]

Equation (12) is applicable whether $b$ and $\tau$ are water or ice equivalent, so long as the same unit is used for both. The straight solid line in Figure 4 expresses this theoretically expected relationship, while the broken line is the statistically calculated regression line for the points. The gradient of the regression line is $-7.85$ and very close to the theoretical prediction of $-8$. The figure demonstrates that the wide range in the variety of the ELA effect on the mean annual specific mass balance can be expressed as a function of the annual mean turnover and surface gradient, both of which are relatively easy to obtain or estimate. One of the main advantages for using the turnover instead of mass balance as a variable is that the turnover is much less variable than mass balance, owing to the complementary relationship between the absolute values of ablation and accumulation. To demonstrate this point, standard deviations of annual specific turnover and annual mean specific mass balance are compared for White Glacier, Ram River Glacier and Kesselwandferner, which represent glaciers of very small, medium and very large mass-balance sensitivity of the ELA, respectively (Table 5). These glaciers also fit very well the theoretical expectation of the relationship of the ELA mass-balance sensitivity with $\tau/\alpha$. This relationship makes it possible to estimate the mass-balance change of a glacier as a result of climatic changes, given the ELA shift, mean turnover and geometry of the glacier.

**CONCLUSIONS**

The climate prevailing at the equilibrium lines is identified as a function of annual total precipitation and summer temperature in the free atmosphere. Refinement of the relationship is possible by introducing global and long-wave net radiation. The equivalent values for temperature, precipitation and radiation at the glacier equilibrium lines are approximately $1^\circ$C, $350$ mm w.e. and $7$ W m$^{-2}$, respectively. Assuming this relationship holds, the effect of a climatic change on the shift of the equilibrium line, and further, the effect of the shift of the equilibrium line on the change in the mean specific mass balance, are evaluated. The sensitivity of the mean specific mass balance is found to be proportional to

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**Table 5. Comparison of the standard deviations of the annual specific turn-over and annual mean specific mass balance for selected glaciers (in mm w.e.)**

<table>
<thead>
<tr>
<th>Glaciers</th>
<th>Standard deviations</th>
<th>Period of observation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Turn-over</td>
<td>Mass balance</td>
<td></td>
</tr>
<tr>
<td>White Glacier</td>
<td>58</td>
<td>266</td>
<td>1959/60–1978/79</td>
</tr>
<tr>
<td>Ram River Glacier</td>
<td>155</td>
<td>540</td>
<td>1965/66–1974/75</td>
</tr>
<tr>
<td>Kesselwandferner</td>
<td>106</td>
<td>295</td>
<td>1965/66–1980/81</td>
</tr>
</tbody>
</table>

*Source references*  
(1) Weiss (1984); (2) Kasser (1973); (3) Müller (1977); (4) Haeberli (1985).
the annual mass turnover and reciprocally proportional to the surface gradient. The proportionality constant is \( -8 \) when the longitudinal length of a glacier is taken as a unit for lengths such as altitude and mass balance. The present work offers a possibility of predicting the mass-balance change of a glacier resulting from a climatic change.

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The accuracy of references in the text and in this list is the responsibility of the authors, to whom queries should be addressed.

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