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On the parameterization of glacier equilibrium line altitude

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Abstract. The equilibrium line altitude (ELA) of a glacier is said to be an important characteristic of the glacier and a parameter representing it should be included in a glacier inventory. However, there are few glaciers whose ELA has been directly measured and furthermore ELAs appear to be highly variable from year to year in comparison with their secular variations. In the present paper, statistical analyses are made of mass balance and ELA time series for 33 glaciers. The steady state ELA is estimated for each glacier and its approximation in terms of simple and, within the context of a glacier inventory, easily measured orometric parameters is tested. In most cases, discrepancies are only a few decametres.

Paramétrisation de la ligne d'équilibre des glaciers

Résumé. La ligne d'équilibre d'un glacier (ELA) est réputée être une caractéristique importante du glacier, et un paramètre qui en soit représentatif devrait figurer dans un inventaire des glaciers. Toutefois, il n'existe que peu de glaciers pour lesquels on ait déterminé directement l'altitude de l'ELA et de plus, les ELA se rélèvent être extrêmement variables d'une année à l'autre, en comparaison de leur variations séculaires. Dans le présent article, il est procédé à des analyses statistiques des séries chronologiques du bilan de masse et de l'ELA de 33 glaciers. L'ELA correspondant au régime stationnaire est estimée pour chaque glacier et son approximation à l'aide de paramètres orographiques simples, facilement mesurables dans le cadre d'un inventaire des glaciers, est testée. Dans la plupart des cas, les écarts ne sont que de quelques décamètres.

INTRODUCTION

By definition, the line separating the ablation area of a glacier from the accumulation area is the equilibrium line (Meier, 1962). The net or annual specific balance is zero along this line and its altitude is denoted by ELA. The ELA is best determined by careful measurement of specific balance quantities at many points on the glacier surface so that reasonably reliable isolines of zero balance may be drawn. The concept of the ELA is only meaningful if the specific balance is a more or less definite function of altitude so that the isoline of zero balance is roughly parallel to the contour lines on the glacier. Such measurements have been made on relatively few glaciers (probably less than one hundred) and, even then, for only a few years; the longest continuing series of ELA and mass balance measurements is from Storglaciären in northern Sweden which started in 1945/1946 (Schytt, 1962).

All known ELA series show great variability from year to year with differences of several hundred metres between maximum and minimum ELA values corresponding to balance years with highly negative or positive mass balances respectively. At the same time, it can be speculated that secular variations of glacier ELAs are only of the order of tens of metres per century. Clearly, inastar as a glacier inventory is supposed to describe the state of glacierization of a region with respect to the secular time scale, it would be wrong to include ELA values for only a single year unless that year can be shown to be 'typical'. As this is difficult to do, it is suggested that the best parameterization of the ELA for the purposes of glacier inventory is the steady state ELA, i.e. the ELA corresponding to a balanced mass budget.

Østrem and Liestøl (1963) determined the steady state ELA for 34 Norwegian glaciers by applying a 'normal' curve of specific balance *versus* altitude to the hypsographic curve of the glacier and shifting the curves relative to each other to achieve a balanced budget. Østrem (1975) determined the steady state ELA for a number of glaciers by linear regression of the observed ELA on the mean specific balance whilst Hoinkes (1970) used a nonlinear curve of unspecified form for Hintereisferner.

The concept of a line on the glacier surface, the firn line, where accumulation of snow is precisely counterbalanced by ablation is an old one. Already in the nineteenth century, the estimation of the altitude of such a line was a subject of controversy in alpine literature, see Brückner (1886), Hess (1904, pp. 67-71) and Gross *et al.* (1976) for brief reviews of the various methods suggested. Although developed on the basis of meagre observational material, some of the methods are still of interest, particularly as the firn line, according to modern definition, is closely related to the equilibrium line on alpine glaciers (Hoinkes, 1970). Of the various empirical methods which have been suggested for the determination of firn line altitudes in the Alps the most important for present purposes are those which can be classified as 'orometric', i.e. based upon altitude-area measurements made on topographic maps. Richter (1885) suggested that the firn line divides the accumulation and ablation areas according to a definite ratio and suggested a value of 8:1 whilst Brückner (1886) proposed a value of 3:1 for the area ratio corresponding to a maximum firn line altitude. An area ratio of 2:1, corresponding to an accumulation area ration (AAR) of 0.67, is now often accepted as approximately valid for the steady state ELA of alpine glaciers under present climatic conditions (Gross *et al.*, 1976).

For the special case of a glacier with a symmetric hypsographic curve and a constant vertical gradient of specific balance, an area ratio of 1:1 (AAR = 0.50) would correspond to a steady state mass balance (Meier and Post, 1962). The corresponding altitude, i.e. of the contour line dividing the glacier area in half, is recommended for inclusion in the World Glacier Inventory by TTS (1977) under the term 'mean' glacier elevation (it is more correctly the 'median').

According to Kurowski (1891) a glacier should be in a steady state condition with a firn line corresponding to the area-weighted mean altitude of the glacier (very close to the true mean altitude) under the simple assumption of a constant vertical gradient of specific balance. Although the latter assumption is generally questionable, the method enjoyed some popularity in the early twentieth century and has been recently rediscovered by Sissons (1974) independently of Kurowski (1891).

Parameters which purport to represent the steady state ELA of a glacier can be easily calculated according to the area ratio method or Kurowski's method if the hypsographic curve of the glacier is known. This in turn, can be determined by planimetry of a topographic map of the glacier, preferably at large scale, if one is available. These orometric parameters will be valid for the state of the glacier depicted on the map and their accuracy will be limited by the quality of the map. However, their validity as approximations of the 'true' steady state ELA can only be tested for those few glaciers where field observations are available. Early investigators could not test them critically because of the lack of such field data.

SOURCES OF DATA AND COMPUTATION OF PARAMETERS

A literature search was carried out to compile the necessary information for as many glaciers as possible, i.e. parallel time series of mean specific balance and equilibrium line altitude (ELA) and information about the area *versus* altitude relation for each glacier. Only series of at least five years were used. In a number of cases such series were available but the hypsographic information was lacking. No distinction between the different systems of defining the balance year was made as long as both the mass balance and the ELA relate to the same year. The main sources of data were the tabulations given in the three publications of the Permanent Service on the Fluctuations of Glaciers (Kasser, 1967, 1973; Müller, 1977). However, these data were treated with caution and, in a number of cases, corrections were made using data from publications by the individual investigators.

The glaciers used in the present study are listed in Table 1 together with information about periods of record and the sponsoring agencies. Despite careful checking, it is likely that errors remain in the data. Measurement errors are of course inherent but, by the nature of the analysis of the raw data, published results are often 'preliminary' and are subsequently 'amended' so that discrepancies between different published sources do arise.

TABLE 1. Steady state ELA (E_0) with 95 per cent confidence interval for 33 glaciers with record lengths of N years

Glacier	Period	N	E_0 [m]	Sponsoring agency
Group I – Arctic North America				
Baby Glacier	1965-71	7*	970∓10	McGill Univ., Montreal, and
White Glacier	1960-75	16	900∓50	Geography Dept., ETH Zürich
Devon Is. Ice Cap	1961-75	13*	970∓60	P.C.S.P., Ottawa
Group II – Western North America				
Ram River Glacier	1966-75	10	2760∓30	Glaciology Division, Ottawa
Peyto Glacier	1965-75	11	2630∓30	Glaciology Division, Ottawa
Woolsey Glacier	1965-75	10*	2240∓40	Glaciology Division, Ottawa
Place Glacier	1965-75	11	2080∓40	Glaciology Division, Ottawa
Sentinel Glacier	1966-75	10	1860∓40	Glaciology Division, Ottawa
Gulkana Glacier	1966-75	10	1720∓30	US Geological Survey
Wolverine Glacier	1966-75	10	1180∓20	US Geological Survey
Blue Glacier	1964-68	5	1860∓90	University of Washington
South Cascade Glacier	1959-75	17	1890∓30	US Geological Survey
Group III – Scandinavia				
Trollbergdalsbreen	1971-75	5	1030∓50	Water & Elec. Board, Oslo
Engabreen	1970-75	6	1160∓40	Water & Elec. Board, Oslo
Hoegtuvbreen	1971-75	5	860∓10	Water & Elec. Board, Oslo
Alfotbreen	1963-75	12*	1200∓30	Water & Elec. Board, Oslo
Nigardsbreen	1963-75	13	1570∓30	Water & Elec. Board, Oslo
Grasubreen	1964-75	11*	2040∓50	Water & Elec. Board, Oslo
Hellstugubreen	1963-75	13	1850∓20	Water & Elec. Board, Oslo
Hardangerjoekulen	1964-75	12	1680∓20	Norwegian Polar Institute
Austre Memurubre	1968-72	5	1910∓90	Water & Elec. Board, Oslo
Storglaciaeren	1947-75	29	1460∓10	Stockholm University
Group IV – Alps				
Griesgletscher	1962-75	14	2840∓50	Department of Hydrology/
Limmerngletscher	1950-75	24*	2680∓30	Glaciology, ETH Zürich
Silvrettagletscher	1960-75	16	2760∓30	
Hintereisferner	1953-75	23	2910∓20	University of Innsbruck
Vernagtferner	1966-75	10	3080∓30	Comm. for Glaciology, Munich
Kesselwandferner	1960-75	16	3100∓10	University of Innsbruck
Langtalferner	1963-70	8	2850∓30	Comm. for Glaciology, Munich
Caresèr	1967-75	9	3080∓10	University of Padua
Group V – Central Asia				
Tsentralny Tuyuksu	1957-74	17*	3730∓10	Acad. Sci. Kazakhstan SSR
Malyy Aktru	1970-74	5	3110∓80	State University of Tomsk

* Record is not continuous.

The steady state ELA was computed for each glacier by linear regression of the ELA series (ELA_i, i = 1 to N) on the mean specific balance series (b_i, i = 1 to N), i.e. by least-squares fitting to the following model:

$$ELA_i = E_0 + kb_i \tag{1}$$

where k is an empirical parameter and E_0 is the value of the ELA for $b_i = 0$. In all cases the coefficient of correlation was high. The 95 per cent confidence interval for E_0 was estimated under the usual assumptions (see Kreyszig, 1970, p. 302). The residuals in the regression models for the glaciers with the longer time series were tested for homogeneity using both Helmert's and Abbe's criteria (Konrad, 1944, pp. 134-135) and, in most cases, can be 'accepted' as homogeneous so that the estimates of the confidence interval for E_0 are reasonably reliable. Values of E_0 and its 95 per cent confidence interval are given in Table 1 (note that all values have been rounded to the nearest 10 m as greater precision seems unjustified). Although they cannot be without error, the computed values of E_0 in Table 1 should be close to the 'true' values of steady state ELA for the various glaciers and periods of record and they can be used as standards to which the orometric parameters can be compared.

For each glacier a table was prepared showing the area within each altitude band of 50 or 100 m thickness and the different orometric parameters were calculated from these. The first of these is Kurowski's parameter which is denoted by E_{MN} and is defined as follows:

$$E_{MN} = \frac{1}{S} \sum_{j=1}^{j=J} S_j \cdot h_j \tag{2}$$

where S_j and h_j are the area and centred-altitude respectively of the jth altitude band and S is the total area of the glacier. Calculated according to (2), E_{MN} will be very close to the true, i.e. arithmetic, mean altitude of the glacier.

Two other orometric parameters are denoted by E_{50} and E_{67} respectively. They are the altitudes above which respectively 50 per cent and 67 per cent of the glacier area are located, i.e. they are altitudes corresponding to AAR values of 0.50 and 0.67. A further parameter was calculated for comparison with the orometric parameters. This is E_{CR} which is defined as the sum of the maximum and minimum altitudes of the glacier divided by 2.

TESTING OF PARAMETERS

The averages of E_0, of the three orometric parameters and of E_{CR} for the five groups of glaciers in Table 1 are given in Table 2. The table shows that there is generally close agreement between E_0 and the various altitude parameters if one is only interested in

TABLE 2. Mean values of steady state ELA and other parameters for 33 glaciers divided into five groups.

Group	No.	E_0 [m]	E_{MN} [m]	E_{50} [m]	E_{67} [m]	E_{CR} [m]
Group I	3	(950)	(1070)	(1130)	(1000)	(940)
Group II	9	2020	2050	2050	1960	2040
Group III	11	1470	1490	1500	1440	1390
Group IV	8	2910	2960	2980	2890	2990
Group V	2	(3420)	(3460)	(3510)	(3410)	(3390)
Groups I-V	33	2040	2080	2100	2010	2030

the whole range of possible steady state ELAs. For example, the spread in average values of the different altitude parameters is only 2010-2100 m compared to the range of E_0 values from 860 to 3730 m in Table 1. However, differences between parameters for individual glaciers can be quite large.

It should be emphasized that the grouping of the glaciers in Table 1 is rather arbitrary, i.e. geographically rather than climatically or according to some glaciological criterion. Nevertheless, there are some interesting differences between the groups. In Group I all three orometric parameters are larger than E_0. This is understandable when one recalls that variation of specific balance with altitude is far from linear on glaciers like White Glacier (see Müller, 1977, pp. 138-145). In general the relationship is roughly linear in the ablation area whilst the specific balance becomes rather constant in the accumulation area which must, therefore, be proportionally bigger to achieve a mass balance of zero. According to this argument one can also expect higher AAR values for glaciers in continental climates as compared to maritime climates which appears, in fact, to be the case.

Means and standard deviations of the differences between E_0 and the three orometric parameters as well as E_{CR} are given in Table 3. The statistics in Table 3 are presented to summarize the data within the various groups, there is no presumption that the groups constitute homogeneous samples: they are certainly not normally distributed.

The parameter E_{CR} is clearly a poor approximation to E_0 overall and will not be considered further in the present paper. It was only included in the study in the first place because it is easier to obtain than the three orometric parameters, as maximum and minimum glacier altitudes are already recommended for inclusion in a World Glacier Inventory (UNESCO/IAHS, 1970).

TABLE 3. **Mean and standard deviation (SD) of differences between steady state ELA and other parameters for 33 glaciers divided into five groups**

		$E_{MN} - E_0$		$E_{50} - E_0$		$E_{67} - E_0$		$E_{CR} - E_0$	
Group	No.	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Group I	3	(+ 120)	–	(+ 180)	–	(+ 50)	–	(– 10)	–
Group II	9	+ 30	± 40	+ 30	± 50	– 70	± 30	+ 10	± 90
Group III	11	+ 10	± 10	+ 30	± 30	– 30	± 30	– 80	± 160
Group IV	8	+ 40	± 30	+ 70	± 40	– 30	± 40	+ 70	± 50
Group V	2	+ 40	–	+ 90	–	(+ 20)	–	(– 30)	–
Groups I-V	33	+ 40	± 40	+ 60	± 60	– 30	± 50	– 10	± 120

It would be tempting to use the results in Table 3 as a basis for choosing the 'best' parameter with which to represent the steady state ELAs of glaciers within each group. For example E_{MN} and E_{50} are equally good for Group II, E_{MN} is best for Group III and E_{67} is best for Group IV and also appears best for Groups I and V on the basis of the scanty data available. However, variations within each group make this approach questionable and, furthermore, the question of the 'representivity' of the glaciers within each group arises.

SECULAR VARIATIONS OF OROMETRIC PARAMETERS

Strictly speaking, information about glacier ELAs only exists for those glaciers and periods where direct measurements have been made. As such measurements have only been made for at most the last 30 years, no definite discussion about secular variations can be ventured. On the other hand, the question of secular variations in the orometric parameters can be examined for those glaciers for which past hypsographic information exists, i.e. glaciers which have been reasonably accurately mapped in the past.

A literature search was made to find suitable hypsographic data for a number of glaciers. Kasser (1967, Tables 16 to 19) and (1973, pp. 233-234 and pp. 237-242) presents data from a number of glaciers which, supplemented where necessary with data from Müller (1977, Table E), enable the orometric parameters to be calculated for various glacier states. The changes in these parameters together with the percentage change in area are given in Table 4 for eight alpine glaciers (note that the sign convention is positive (+) for increase with time and negative (−) for decrease). Although there are often large differences between the values of the different parameters for the same glacier state, the changes in parameters between states seem quite consistent as shown by the mean values in Table 4 (the mean values are only given for this comparison and, calculated in this way, have no glaciological or climatological meaning).

TABLE 4. Secular variations of glacier area S and three orometric parameters for eight alpine glaciers

Glacier	Period	ΔS [%]	ΔE_{MN} [m]	ΔE_{50} [m]	ΔE_{67} [m]
Griesgletscher	1925-1961	− 15	+ 16	+ 29	+ 37
	1961-1975	− 6	+ 14	+ 17	+ 26
Limmerngletscher	1945-1959	− 10	+ 8	+ 4	+ 13
	1959-1975	0	− 9	− 3	− 6
Silvrettagletscher	1938-1956	− 11	+ 16	+ 15	+ 21
	1956-1975	− 5	+ 9	+ 11	+ 6
Allalingletscher	1932-1946	− 3	+ 26	+ 5	+ 26
	1946-1956	− 4	+ 17	+ 8	+ 11
	1956-1967	0	+ 11	+ 3	+ 3
Rhonegletscher	1882-1973	− 17	+ 26	+ 6	+ 12
Hintereisferner	1953-1962	− 1	+ 13	+ 17	+ 19
	1962-1975	− 8	+ 13	+ 10	+ 8
Vernagtferner	1889-1912	0	− 9	− 9	− 11
	1912-1938	− 9	+ 16	+ 6	+ 11
	1938-1969	− 9	+ 16	+ 14	+ 15
Guslarferner	1889-1912	− 3	+ 1	− 1	+ 2
	1912-1938	− 11	+ 8	+ 3	+ 7
	1938-1969	− 19	+ 25	+ 24	+ 27
Mean value			+ 12	+ 9	+ 13

The question of whether the changes in Table 4 represent real changes in steady state ELA is problematic. For example, they are all computed from the same hypsographic information so that they will all be influenced by similar errors. More seriously, there is no evidence that the relationship between steady state ELA and any particular parameter remains invariant. For example the steady state AAR in one state might be very close to 0.67 and close to 0.50 in a subsequent state: until a theory exists to relate AARs or 'best' orometric parameters to climatic and topographic factors the assumption of an invariant 'rule' for computing steady state ELAs will remain open to question. It is frequently used in the absence of anything better, for examples see Callender (1950), Sissons (1974) and Gross *et al.* (1976). At the same time, it is dangerous to compare ELAs calculated for different times using different methods.

Bearing in mind the above limitations, the results in Table 4 suggest that secular variations in steady state ELAs may be quite small even when variations in glacier areas and tongue elevations are marked. This has also been suggested by Müller *et al.* (1976, pp. 24-25) on the basis of a comparison between results of the Swiss glacier inventory and those presented by Jegerlehner (1903).

IMPLICATIONS FOR A WORLD GLACIER INVENTORY

One or more parameters should be included in glacier inventories as measures of the equilibrium line altitude. According to the findings of the present study, reasonably good approximations can be obtained with all three orometric parameters and, as long as errors of a few tens of metres are acceptable, it does not really matter which one is used. The elevation dividing the glacier area in half, i.e. E_{50} in the present paper, is in fact recommended by TTS (1977). Its determination is marginally easier than the determination of the true mean altitude E_{MN}. It is also better defined and more generally applicable, and possibly more accurate, than the methods recommended in the original guide (UNESCO/IAHS, 1970, p. 15).

However, as it appears that secular variations in equilibrium line altitude are quite small, care should be taken that any orometric parameter entered into a glacier inventory is determined with as high an accuracy as is justified by the available cartographic information. Furthermore, parameters should not be 'mixed', i.e. a consistent definition should be used so that comparisons can be made between glacier inventories to study variations in both time and space.

A theory relating equilibrium line altitudes to climatic and orographic factors is required. As the hypsographic curve of a glacier can be taken as 'input' data, the problem will be to develop an understanding of the vertical variations of specific balance on glaciers under different climatic conditions. This need was already recognized at the end of the last century and it is now time to take up the challenge seriously.

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DISCUSSION

Meier:
Where did you get the number 0.67?

Braithwaite:
There is no theoretical justification for this but it seems to have become accepted as an average AAR value for alpine glaciers in a steady state condition. I refer you to the paper in *Zeitschrift für Gletscherkunde* (1976) by Gross, Kerschner and Patzelt.

Meier:
Your statistics appear to suggest that 0.60 to 0.62 might produce excellent agreement.

Braithwaite:
Yes, I remember that Post and Meier suggested exactly those values in 1962 for glaciers in western North America.

Meier:
Also, I'd like to ask you more about AARs.

Braithwaite:
We converted our steady state ELAs into AARs but we got some funny results. The average steady state AARs were 0.72 for arctic North America, 0.54 for western North America, 0.59 for Scandinavia and 0.62 for the Alps. These values seem rather low to me except for the first one.

Radok:
What is your definition of 'steady state ELA'?

Braithwaite:
It is simply an estimate of the ELA corresponding to a value of zero for the mean

specific balance. We calculated it by linear regression of observed ELA time series onto mean specific balance series.

Müller:
For the steady state condition not only must the mean specific balance be zero but also there must be no change of geometry, i.e. no advance or retreat.

Braithwaite:
You are perfectly correct and this should be taken account of in the regression equation. However, none of the series are longer than 30 years and the secular variations of the orometric parameters seem very small so that I think we can afford to ignore this effect in the present context.