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MODELING MASS-BALANCE CHANGES DURING A GLACIATION CYCLE

by

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ABSTRACT

Identification of present-day climate setting and alpine glacier-balance gradients indicates that the balance gradient of alpine glaciers is primarily determined by climatic conditions. Determination of balance gradients for specific climatic settings on present-day ice sheets provides an analog for determining the mass balance on paleo and future ice sheets.

INTRODUCTION

Mass balance is a primary variable determining the size, height, and shape of ice sheets. One of the fundamental inputs to ice-sheet models is surface mass balance. In order to construct or reconstruct ice sheets the temporal and spatial variation of mass balance must be known. The surface mass balance on an ice sheet is determined by climatic conditions. To determine the mass balance at a given point requires knowing the climatic conditions and elevation of that point. This paper describes a method for determining the temporal and spatial variations of mass balance for ice-sheet reconstructions. Unfortunately, there is no satisfactory equation relating mass balance to specific climate variables. It is equally impossible to specifically determine the climate conditions for the past and the future. However, GCMs and proxy climate records do allow the general climate setting to be identified. Climate settings represent a range of climatic conditions.

Reconstructions of ice sheets have typically relied on mass-balance models based either on mass-balance distribution over the Antarctic ice sheet or Greenland ice sheet, or on the present distribution of precipitation adjusted for ice-age conditions. In reality, the balance gradient of an ice sheet is determined by climate. Thus, climatic setting should be used for reconstructing ice-sheet mass-balance patterns.

BALANCE GRADIENT CONSTRUCTION

The balance gradient of a glacier is the change in balance with altitude. Published balance gradients (Table I) for present-day alpine glaciers, where the climate setting is known, cluster into five distinct populations. Cluster analysis indicates that 81% of the alpine glaciers can be accurately assigned to one of the five populations. The five climate settings were chosen to provide the best fit to the data. Each of the five populations is a distinct climatic regime: (1) temperate maritime, (2) sub-polar maritime, (3) sub-polar mix, (4) polar mix, (5) polar continental (Fig. 1). In addition, a polar desert climatic zone exists over the interior of Antarctica. Each climate zone is typified by temperatures ranging from temperate to polar and by precipitation ranging from maritime to continental (Table II). The sub-polar mix and polar mix climate zones are distinguished by ELA more than by a balance-gradient change. The fact that alpine glacier balance gradients are grouped climatically

TABLE I. BALANCE GRADIENT ($B(n)$) OF SELECTED ALPINE GLACIERS. BALANCE GRADIENTS ARE REPORTED IN cm 100 m^{-1}. CLIMATE SETTING, LATITUDE AND REFERENCE FOR THE BALANCE-GRADIENT INFORMATION ARE ALSO LISTED

No.	Glacier	Zone	$B(n)$	Lat.	References
1	Taku	SM	87	58	Mayo, 1984
2	Lemon	SM	120	58	Mayo, 1984
3	Berendon	SM	90	56	Mayo, 1984
4	Columbia	SM	94	61	Mayo, 1984
5	Malaspina	SM	85	60	Mayo, 1984
6					
7	Mendenhall	SM	80	58	Pelto, 1987
8	Wolverine	SM	105	63	Mayo, 1984
9	Vatnajökull	SM	80	64	Ahlmann, 1948
10	Nigardsbreen	SM	97	61	Schytt, 1969
11	Engabreen	SM	83	67	Schytt, 1969
12	Ålfotbreen	SM	100	61	Schytt, 1969
13	Storbreen	SM	88	61	Schytt, 1969
14	Hamberg	SM	75	54	Smith, 1960
15					
16	Hodges	SM	90	54	Smith, 1960
17	Trollsbergdalsbreen	SM	68	66	Østrem and others, 1979
18	Høgtvubreen	SM	80	66	Østrem and others, 1979
19	Hardangerjökull	SM	78	60	Østrem and others, 1979
20	Austre Memurubre	SM	73	62	Østrem and others, 1979
21	Hoffellsjökull	SM	75	67	Ahlmann, 1948
22	Bondhusbreen	SM	80	60	Østrem and others, 1979
23	Folgefonni	SM	100	60	Østrem and others, 1979
24	Tunsbergdalsbreen	SM	70	66	Østrem and others, 1979
25	Nisqually	TM	150	48	Mayo, 1984
26	South Cascade	TM	145	49	Mayo, 1984
27	Blue	TM	120	49	Mayo, 1984
28	Rainbow	TM	110	49	Pelto, 1988
29	Lynch	TM	160	48	Pelto, 1988
30	Columbia	TM	160	48	Pelto, 1988
31					
32	Sentinel	TM	120	51	Braithwaite, 1984
33	Vestfonna	PX	40	79	Schytt, 1964
34	Frøyabreen	PX	45	74	Ahlmann, 1948
35	Fjortende Julibreen	PX	36	79	Ahlmann, 1948
36	Qamanârssûp sermia	PX	43	64	Braithwaite, 1986
37	Narssaq	PX	52	61	Weidick, 1984
38	Valhaltindegletscher	PX	34	61	Weidick, 1984
39	Hellstugubreen	PX	35	61	Østrem and Pytte, 1969
40					
41	Austfonna	PX	42	79	Schytt, 1964
42	Vøringbreen	PX	45	78	Guskov and Troitskiy, 1984
43	Bogerbreen	PX	36	78	Guskov and Troitskiy, 1984

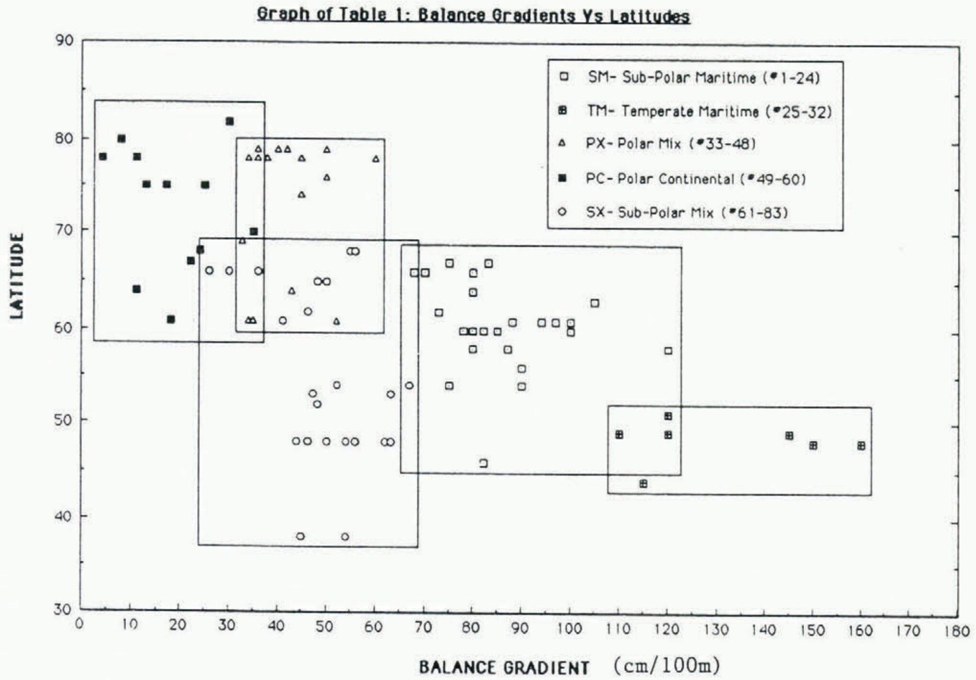

Fig. 1. Balance gradient of alpine glaciers versus latitude. Balance gradient is in cm 100 m^{-1}; this is a standard unit of reporting.

No.	Glacier	Zone	$B(n)$	Lat.	References
44	Longyearbreen	PX	34	78	Guskov and Troitskiy, 1984
45	Daudbreen	PX	38	78	Guskov and Troitskiy, 1984
46	Bertilbreen	PX	60	78	Guskov and Troiskiy, 1984
47	Laika Ice Cap	PX	50	76	Blatter and Kappenberger, 1988
48	Lilliehöökbreen	PX	50	79	Ahlmann, 1939
49	Nunatarssuaq	PC	25	75	Weidick, 1984
50	Baby	PC	30	82	Braithwaite, 1984
51	Devon	PC	8	80	Braithwaite, 1984
52	Decade	PC	11	78	Braithwaite, 1984
53	McCall	PC	24	68	Mayo, 1984
54	Hazen	PC	17	25	
55	Taylor	PC	4	78	Robinson, 1984
56	Barnes	PC	35	70	Baird, 1952
57	Penny	PC	22	67	Koerner, 1979
58	White	PC	13	75	Braithwaite, 1984
59	Gråsubreen	PC	18	61	Schytt, 1967
60	James Ross Island	PC	11	64	Aristarain and others, 1987
61	Sonneblickes	SX	44	48	Braithwaite, 1984
62	Vernagtferner	SX	56	48	Braithwaite, 1984
63	Kesselwandferner	SX	63	48	Braithwaite, 1984
64	Hintereisferner	SX	50	48	Braithwaite, 1984
65	Caréser	SX	62	48	Braithwaite, 1984
66	Silveretta	SX	54	48	Braithwaite, 1984
67	Malaiy	SX	45	38	Dyugerov and others, 1988
68	Peyto	SX	52	54	Braithwaite, 1984
69	Place	SX	47	53	Braithwaite, 1984
70	Woolsey	SX	48	52	Braithwaite, 1984
71	Ram River	SX	63	53	Braithwaite, 1984
72	Saskatchewan	SX	67	54	Braithwaite, 1984
73	Storglaciären	SX	55	68	Braithwaite, 1984
74	Tuyuksu	SX	54	38	Braithwaite, 1984
75					
76	Blåisen	SX	36	66	Østrem and Pytte, 1969
77	Cainhavarre	SX	30	66	Østrem and Pytte, 1969
78	Storsteinsfjellbreen	SX	26	66	Østrem and Pytte, 1969
79	Vestre Memurubre	SX	46	62	Østrem and Pytte, 1969
80	Vesledalsbreen	SX	50	65	Østrem and Pytte, 1969
81	Kårsa	SX	56	68	Schytt, 1969
82	Limmerngletscher	SX	46	48	Braithwaite, 1984
83	Nordbogletscher	SX	41	61	Weidick, 1984

TABLE II. CLIMATIC CONDITIONS ASSOCIATED WITH EACH OF THE FIVE CLIMATE SETTINGS

Climate zone	Winter temperature	Summer temperature	Annual precipitation
	°C	°C	m
Polar continental	<−20	<8	<0.4
Polar mix	<−15	<6	0.4−1.0
Sub-polar mix	−10 to −15	8−12	0.6−1.2
Sub-polar maritime	−6 to −12	6−10	>1.2
Temperate maritime	0 to −6	10−16	>1.5

indicates that the balance gradient is determined by its climate setting (Schytt, 1967). Hence, if the climatic setting can be identified, then the mean balance gradient of local alpine glaciers can be determined.

The climate setting is determined at the margin of the glacier. This method was used for two reasons: (1) this is where most weather records and proxy climate data exist. (2) mass-balance distribution on present-day glaciers is determined by the regional climate setting, which reflects the regional air masses. The air masses are modified by the ice sheet. For this reason, above 2400 m all of the balance curves approach a polar continental climate setting. Below 2400 m, the climate setting at the margin determines the balance gradient. Above 2400 m, the climate setting over ice sheets is polar continental.

TABLE III. SOURCES FOR MASS-BALANCE VERSUS ELEVATION DATA USED TO FIT THE BALANCE GRADIENTS FOR EACH CLIMATE ZONE

Climate zone	Data sources
PC	Baird, 1952; Benson, 1962; Koerner, 1979; Giovinetto and Bentley, 1985; Aristarain and others, 1987; Blatter and Kappenberger, 1988
PX	Ahlmann, 1939, 1948; Schytt, 1964; Weidick, 1984; Braithwaite, 1986; Kostecka and Whillans, 1988
SX	Benson, 1962; Weidick, 1984; Braithwaite, 1986
SM	Ahlmann, 1939, 1948; Smith, 1960
TM	Ahlmann, 1939; Mayo, 1984; Pelto, 1987

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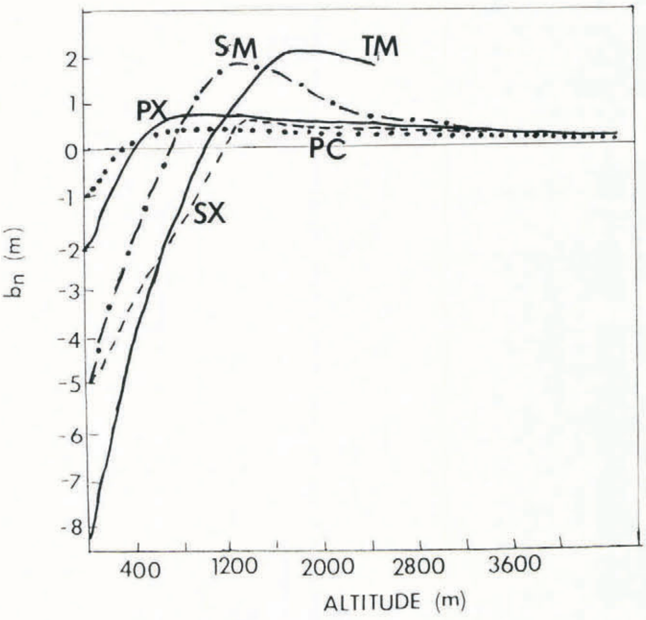

Fig. 2. The balance curve obtained by application of Equation (1) to available ice-sheet and ice-cap mass-balance data.

Mass-balance variations within a climate zone are determined primarily by elevation. Thus a mass-balance equation must be able to calculate mass balance from elevation. Data of mass-balance changes with elevation from ice caps and ice sheets in each of the five climate zones are used to reconstruct a mean balance gradient for that zone. Data sources are indicated in Table III. Data are not used from alpine glaciers because of the steep slopes that cause large fluctuations in orographic precipitation and hence mass balance. A least-squares fit is used to obtain the most representative balance gradient for the cloud of data points from each climate zone. It is not necessary to use least squares to obtain a good fit, but least squares did provide the best fit. Equation (1) is used to obtain best-fit balance gradients:

$$A(h) = A_1 e^{-x_1 h^2} + A_2 e^{-x_2 h^2} \qquad (1)$$

where h (m) is the altitude of the previous time step, A_1 (m) is ablation at the margin, A_2 (m) is accumulation at the margin, x_1 m m^{-1} is the decay exponent of ablation with elevation, and x_2 m m^{-1} is the decay exponent of accumulation with elevation.

The constants obtained for each climate zone are shown in Table IV and the balance gradients in Figure 2. Figure 3 shows the balance gradient for polar continental conditions, and the data points used. In constructing ice sheets at a given time step, the elevation of the ice sheet is known at the previous time step. At the first time step the elevation is the bedrock elevation.

Distance from the margin, though an important mass-balance parameter, is secondary to the effect of elevation.

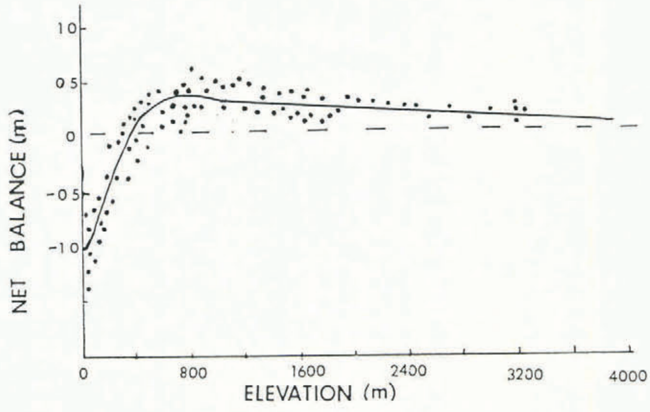

Fig. 3. The balance curve for the polar continental climate setting, with data points indicated. Dashed lines are the equilibrium lines.

The distance of importance is the distance to the primary moisture source measured along the transport path. This distance is seldom known. Thus, although distance from the margin influences mass balance, it cannot be included in the time-dependent finite element, because accurate determination for paleo or future ice sheets is not possible. Even attempting to utilize this parameter in duplicating present-day Antarctic mass balance has proven problematic. On ice sheets the elevation is strongly related to the distance from the edge of the ice sheet. Because the ice-elevation term is squared in Equation (1) the distance from the ice-sheet margin though not directly included is implictly included in Equation (1).

The mass balance of an ice sheet during a glaciation cycle varies depending on the climatic setting. In particular the climatic setting below the ELA changes. The majority of the accumulation zone remains either in a polar continental or a polar desert climate zone. Ice sheets are most susceptible to changes in ablation because the ranges in ablation values are several times larger than for changes in accumulation (Ahlmann, 1948; Schytt, 1967; Weidick, 1984). An example is Jakobshavns Isbræ, where peak accumulation is 0.6 m a^{-1} and ablation at the margin is 6.0 m a^{-1}. Peak ablation is an order of magnitude larger than peak accumulation, and the annual variation of ablation is an order of magnitude larger. This is especially true with respect to ice thickness near the margin. Hence, accurate ice-sheet reconstruction requires knowing the climatic setting in the ablation zone.

Mass-balance changes with time are caused primarily by changes in climatic setting. However, mass balance does change within climate zones, due to changes in the surface heat budget, caused by changes in atmospheric composition, changes in albedo, and changes of incoming solar insolation. The resulting changes in the balance gradient are represented by changes in ELA for each balance gradient. The shape of the balance gradient does not change, only the ELA shifts. That this is actually what happens is demonstrated by changes in climate such as the Little Ice Age. During the Little Ice Age climate zones did not change but ELA were reduced by 150–250 m (Denton and Karlén, 1975).

TABLE IV. THE CONSTANTS USED IN EQUATION (1) TO CONSTRUCT THE BALANCE GRADIENT FOR EACH CLIMATE ZONE. A_1 AND A_2 ARE THE ABLATION AND ACCUMULATION AT THE MARGIN, RESPECTIVELY. X_1 AND X_2 DETERMINE THE CHANGES IN ABLATION AND ACCUMULATION WITH ELEVATION

Climate zone	A_1	A_2	X_1	X_2	ELA
	m	m	m m^{-1}	m m^{-1}	m
PC	−1.2936	0.2998	1.5023×10^{-6}	3.6194×10^{-8}	312
PX	−2.8490	0.8378	8.5345×10^{-6}	3.0453×10^{-8}	379
SM	−7.5768	2.5689	2.7733×10^{-6}	2.9162×10^{-7}	660
SX	−5.8563	0.8575	1.3228×10^{-6}	9.4618×10^{-8}	1250
TM	−11.6877	3.67407	1.0838×10^{-6}	3.6411×10^{-8}	1050

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The above method is fully quantitative and is based solely on all available data. With this method the mass-balance distribution can be calculated once the climate setting is determined from proxy records and GCM results. The climate settings and balance gradients used are not ideal; however, they do produce good results based upon all currently available data. The main weakness of this method is in the dome regions, where climate and mass-balance relationships are poorly known.

REFERENCES

Ahlmann, H.W. 1948. *Glaciological research on the North Atlantic coasts*. London, Royal Geographical Society. (R.G.S. Research Series 1.)

Ahlmann, H.W. and S. Thorarinsson. 1939. Vatnajökull. Scientific results of the Swedish–Icelandic investigations 1936–37–38. Chapter VI. The accumulation. *Geogr. Ann.*, **21**(1), 39-66.

Aristarain, A.J., J.F. Pinglot, and M. Pourchet. 1987. Accumulation and temperature measurements on the James Ross Island ice cap, Antarctic Peninsula, Antarctica. *J. Glaciol.*, **33**(115), 357-362.

Baird, P.D. 1952. The glaciological studies of the Baffin Island expedition, 1950. Part 1: Method of nourishment of the Barnes Ice Cap. *J. Glaciol.*, **2**(11), 2-9.

Benson, C.S. 1962. Stratigraphic studies in the snow and firn of the Greenland ice sheet. *CRREL Rep.* 70.

Blatter, H. and G. Kappenberger. 1988. Mass balance and thermal regime of Laika ice cap, Coburg Island, N.W.T., Canada. *J. Glaciol.*, **34**(116), 102-110.

Braithwaite, R.J. 1984. Can the mass balance of a glacier be estimated from its equilibrium-line altitude? *J. Glaciol.*, **30**(106), 364-368.

Braithwaite, R.J. 1986. Assessment of mass-balance variations within a sparse stake network, Qamanârssûp sermia, West Greenland. *J. Glaciol.*, **32**(110), 50-53.

Denton, G.H. and W. Karlén. 1973. Holocene climatic variations — their pattern and possible cause. *Quat. Res.*, **3**(2), 155-205.

Dyurgerov, M.B., M.G. Kunakhovich, I.F. Khmelevskoy, and Yu.B. Shurdumov. 1988. Osobennosti vneshnego massoobmena Lednika Malyy Azau na El'bruse [Peculiarities of the external mass balance of Malyy and Azau glaciers, the El'brus]. *Mater. Glyatsiol. Issled.* 61, 91-95.

Giovinetto, M.B. and C. Bull. 1987. Summary and analysis of surface mass balance compilations for Antarctica 1960–1985. *Ohio State University. Byrd Polar Research Center. Report* 1.

Gus'kov, A.S. and L.S. Troitskiy. 1984. Vodno-ledovyy balanslednikov Shpitsbergena v 1980/81 i 1981/82 balansovykh godakh [Water–ice balance of Spitsbergen glaciers in the 1980/81 and 1981/82 balance years]. *Mater. Glyatsiol. Issled.* 51, 247-250.

Koerner, R.M. 1979. Accumulation, ablation, and oxygen isotope variations on the Queen Elizabeth Islands ice caps, Canada. *J. Glaciol.*, **22**(86), 25-41.

Kostecka, J.M. and I.M. Whillans. 1988. Mass balance along two transects of the west side of the Greenland ice sheet. *J. Glaciol.*, **34**(116), 31-39.

Mayo, L.R. 1984. Glacier mass balance and runoff research in the U.S.A. *Geogr. Ann.*, **66A**(3), 215-227.

Østrem, G., B. Wold, and K. Repp. 1979. *Glasiologiske undersökelser i Norge 1978*. Oslo, Norges Vassdrags-og Elektrisitetsvesen.

Østrem, G. and R. Pytte. 1969. *Glasiologiske undersökelser i Norge 1968*. Oslo, Norges Vassdrags-og Elektrisitetsvesen.

Pelto, M.S. 1987. Mass balance of south-east Alaska and north-west British Columbia glaciers from 1976 to 1984: methods and results. *Ann. Glaciol.*, **9**, 189-194.

Pelto, M.S. 1988. The annual balance of North Cascade glaciers, Washington, U.S.A., measured and predicted using an activity index method. *J. Glaciol.*, **34**(117), 194-199.

Pelto, M.S., T.J. Hughes, and H.H. Brecher. 1989. Equilibrium state of the Jakobshavns Isbræ, West Greenland. *Ann. Glaciol.*, **12**, 127-131.

Robinson, P.H. 1984. Ice dynamics and thermal regime of Taylor Glacier, south Victoria Land, Antarctica. *J. Glaciol.*, **30**(105), 155-160.

Schytt, V. 1964. Scientific results of the Swedish glaciological expedition to Nordaustlandet, Spitsbergen, 1957 and 1958. *Geogr. Ann.*, **46**(3), 243-281.

Schytt, V. 1967. A study of "ablation gradient". *Geogr. Ann.*, **49A**(2–4), 327-332.

Smith, J. 1960. Glacier problems in South Georgia. *J. Glaciol.*, **3**(28), 707-714.

Weidick, A. 1984. Studies of glacier behaviour and glacier mass balance in Greenland — a review. *Geogr. Ann.*, **66A**(3), 183-195.

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