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Article

Climate on the Blanca Massif, Sangre de Cristo Mountains, Colorado, USA, during the Last Glacial Maximum

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Supplementary Material for Review

Compilation and analysis of melt factors

Melt (or degree-day) factors for snow and ice are required for temperature-index modeling of ablation. Values used in the accompanying paper are based on correlations between point measurements of melt and positive degree-days, or through calibration using net surface ablation available in the literature as listed in Table S1. Care was taken in the selection of values, where possible, so as to avoid values: (1) derived from ablation measurements made in "extreme" environments, specifically in Antarctica, tropical settings, and at extremely high elevations (> 4500 m); (2) used in enhanced temperature-index models where solar radiation is taken into account; (3) derived via tuning to reproduce *regional* basin-wide melt and/or runoff; (4) derived using a melt threshold significantly different that 0 or 1 °C; (5) where it is unclear whether ablation of ice or snow was measured; and/or (6) measured on debris-rich surfaces. Finally, in studies where melt factors were determined at several locations on an individual glacier, or several (nearby) glaciers over the same general time interval (if given), a single mean value is listed with its standard deviation.

Table S1. Compilation of melt (degree-) day factors (mm °C^{-1} d^{-1}) arranged from lowest to largest values. Note that a glacier and corresponding reference will occur more than once if values were obtained at substantially different times. Original source is given where values were cited in another work. Standard deviations are provided if given in source, or when multiple values were averaged.

Location	Ice, ice and snow Melt factors and standard deviation		Original source (where applicable)	Reference	Comments
	Ice	Snow			
Batura Glacier, Karakoram	3.4			[1]	
Bench Glacier, Coast Range, Canada	4.2	2.8		[2]	Reported means
Bridge Glacier, Coast Range, Canada	4.2	3.2		[2]	
Sykora Glacier, Coast Range, Canada	4.2	3.3		[2]	
Lemon Glacier, Alaska	4.5	3.6		[3]	
Woolsey Glacier, Canadian Rockies	4.6	3.2		[2]	
Place Glacier, Coast Range, Canada	4.7	2.7		[2]	
Tiedemann Glacier, Coast Range, Canada	4.8	3		[2]	
Blöndujökull, Kvíslajökull, Iceland	5	4.5		[4]	
Hailuogou Glacier, Hengduan Mountains	5			[1]	
Glacier de Saint-Sorlin, Glacier de Gébroulaz, Glacier de Argentiére, Mer	5 ± 0.4	4.2 ± 0.5		[5]	Mean, 4 values ice, snow

de Glace, French Alps					
Rembeddalsskåka, Norway	5.2	3.4		[6]	
Helm Glacier, Coast Range, Canada	5.3	3.6		[2]	
Storbreen, Norway	5.3	4		[6]	
Engabreen, Norway	5.4	3.4		[6]	
Storbreen, Norway	5.5		Liestøl, 1967	[7]	
Nigardsbreen, Norway	5.5	4	Laumann and Reeh, 1993	[7]	
Hellstugubreen, Norway	5.5	3.5	Laumann and Reeh, 1993	[7]	
John Evans Glacier, Canada	5.5	3.3 ± 0.8	Arendt and Sharp, 1999	[8]	Mean, 2 values, snow
Taku Glacier, Alaska	5.5	2.3		[3]	
Various Norwegian glaciers	5.5		Braithwaite, 1977	[7]	
White Glacier, Arctic Canada	6.4			[9]	
Peyro Glacier, Canadian Rockies	5.6	2.3		[2]	
Ålfobreen, Norway	5.6	4.1		[6]	
Mendenhall Glacier, Alaska	5.7	4.6		[10]	
Keqicar Baqi Glacier, Tien Shan	5.8 ± 1.8			[1]	Mean, 2 values
White Glacier, Arctic Canada	5.8			[9]	
Han Tausen Land, North Greenland	5.9		Braithwaite et al., 1998	[7]	
Storglaciären, Sweden	5.9 ± 0.7		Hock, 1999	[8]	Mean, 2 values, ice
Franz Josef Glacier, New Zealand	6	3	Woo and Fitzharris, 1992	[7]	
Ålfotbreen, Norway	6	4.5	Laumann and Reeh, 1993	[7]	
Storglaciären, Sweden	6	3.2	Hock, 1999	[8]	
Various Swiss glaciers	6		Kasser, 1959	[7]	Reported mean value
Sverdrup Glacier, Arctic Canada	6			[9]	
Glacier de Saint-Sorlin, Glacier de Gébroulaz, Glacier de Argentiére, Mer de Glace, French Alps	6.1	3		[11]	Reported means
Glacier de Saint-Sorlin, French Alps	6.1			[12]	
Glacier de Sarennes, French Alps	6.2	3.8	Vincent and Vallon, 1997	[7]	
South Cascade Glacier, United States	6.2			[13]	
Supphellebreen, Norway	6.3		Orheim, 1970	[7]	
Glaciers 29-31, Northeast Siberia	6.3	2.6		[14]	Mean of listed range
Nigardsbreen, Norway	6.3	4.7		[6]	
Nigardsbreen, Norway	6.4	4.4	Jóhannesson et al., 1995	[7]	
Glacier de Saint-Sorlin, French Alps	6.4	4		[15]	
Rhonegletscher, Swiss Alps	6.6 ± 0.6	5.2 ± 0.8		[16]	Mean, 5 values ice, snow
Lirung Glacier	6.6			[17]	Debris-free ice
Rakiot Glacier, Himalaya	6.6			[17]	Debris-free ice
Rabots Glaciär, Sweden	6.8	4.7		[18]	
Qiongtailan Glacier, Tien Shan	6.8 ± 2.1	3.4		[1]	Mean, 3 values ice
Glacier de la Plaine Morte, Swiss Alps	6.8 ± 0.9			[19]	
Moreno Glacier, Patagonia	7		Takeuchi et al., 1996	[7]	Mean of given range
Koryto Glacier, Kamchaka	7	4.7		[20]	
Glaciar Perito Moreno, Patagonia	7 ± 0.8			[21]	Mean, 5 values
Glacier de Sarennes, French Alps	7 ±0.2	4.1		[22]	Mean, 2 values ice

Glacier Upsala, Patagonia	7.1			[23]	
Glaciar Perito Moreno, Patagonia	7.1			[23]	
Storglaciaren, Sweden	7.1 ± 0.1	7.2 ± 0.6		[24]	Mean, 2 values
Franz Josef Glacier, New Zealand	7.2 ± 0.2	4.6 ± 0.5		[25]	
Qamanârssûp sermia, West Greenland	7.3	2.8	Jóhannesson et al., 1995	[7]	
Ürümqi No. 1 Glacier, Tien Shan	7.3		Lui et al., 1996	[1]	
Hofsjökull, Iceland	7.3	5.3		[26]	
Dokriani Glacier, Himalaya	7.4	5.7	Singh et al., 2000	[8]	
Ålfotbreen, Norway	7.5		NVE, 1965	[4]	
Storsteinsfjellbreen, Norway	7.5			[27]	
Illvi∂rajökull, Iceland	7.6	5.6		[4]	
Gran Campo Nevado Ice Cap, Patagonia	7.6			[28]	
Sátujökull, Iceland	7.7	5.6	Jóhannesson et al., 1995	[7]	
Qamanârssûp sermia, Greenland	7.7			[29]	
White Glacier, Arctic Canada	7.8			[9]	
John Evans Glacier, Canada	7.9 ± 0.4	4.5±0.9	Arendt and Sharp, 1999	[8]	Mean, 2 values ice, 3 snow
Qamanârssûp sermia, Greenland	7.9			[29]	
Universidad Glacier, Chile	8	2.9		[30]	
Nordbogletscher, West Greenland	8.1	2.9	Braithwaite, 1995	[7]	
Qamanârssûp sermia, West Greenland	8.3	3.7	Braithwaite, 1995	[7]	
Ürümqi No. 1 Glacier, Tien Shan	8.5	3.1	Lui et al., 1996	[1]	
Rhonegletscher, Swiss Alps	8.5 ± 0.8			[19]	
Koxkar Glacier, Tianshan Mountains, China	8.8			[31]	Mean value
Urumqi Glacier No. 1, Tianshan, China	8.9	2.7		[32]	
Greisgletscher, Swiss Alps	8.9			[7]	
Storstrømmen, Northeast Greenland	9.3			[33]	Reported mean
Martial Este Glacier, Argentina	9.4	4.7		[34]	
Greenland Ice Sheet	9.5 ± 3.5		Schytt, 1955	[8]	Mean, 2 values
Kronprins Christian Land, North Greenland	9.8		Braithwaite et al., 1998	[7]	
Findelgletscher, Swiss Alps	11.4 ± 1.8			[19]	
Aletschgletscher, Swiss Alps	11.7	5.3	Lang, 1986	[8]	
Langjökull, Iceland	11.9	10.1		[35] Mean, 5 values ice, snow	
Greenland Ice Sheet (margin)	12.6 ± 6.4		Van der Wal, 1992	[8] Mean, 3 values	
Spitsbergen	13.8		Schytt, 1964	[7]	
Vestri Hagafellsjökull, Iceland	14 ± 1.8	11.8 ± 1.0		[24] Mean, 4 values	
Kongsvegen Glacier, Spitzbergen	14.1 ± 2.8	11.2 ± 2.2		[36]	
Greenland	15	3		[37]	
Brúarjökull, Iceland	15.1			[38]	Mean, 2 values ice
Greenland Ice Sheet	18.6		Ambach, 1963	[7]	
Snow only					
Australian Alps		2.9		[39]	
Fillefjell, Norway		3.9	Furmyr and Tollan, 1975	[4]	
Saint Sorlin Glacier, French Alps		4		[40]	
Columbia Glacier, Alaska		4.1		[41]	
66 glaciers		4.1 ± 1.4		[42]	Mean, high, low estimates
Andrews Glacier, United States		4.3		[43]	

Weissfluhjoch, Swiss Alps		4.5	De Quervain, 1979	[7]
Weissfluhjoch, Swiss Alps		4.5	Zingg, 1951	[7]
Dokriani Glacier, Himalaya		5.9	Singh and Kumar, 2000	[8]
Mean	**7.3 ± 2.7**	**4.3 ± 1.8**		
Median	**6.7**	**4**		
Interquartile range	**5.6–7.9**	**3.2–4.6**		

Table S1 shows that a large variation exists for the value of melt factors (m_f), ranging from 3.4 to 18.6 mm °C^{-1} d^{-1} for ice and 2.3 to 11.3 mm °C^{-1} d^{-1} for snow (most published studies report values in these units). These variations reflect for example, the influence and interrelationships among local topographic setting, the relative importance of components of the energy balance (e.g. radiation, sensible heat transfer, turbulence), and the nature of the melting surface (e.g. albedo, roughness). Additionally, difference exist in the length of observations (thus temporal variation), source(s) of temperature data (on or off glacier, distance to meteorological station), calculation of mean daily temperature, determination of lapse rates, whether snow/rain events during the ablation season were accounted for, and so forth [8,44,45]. Nevertheless, the mean values are 7.3 ± 2.7 mm °C^{-1} d^{-1} for ice (n = 92) and 4.3 ± 1.8 mm °C^{-1} d^{-1} for snow (n = 61).

The distributions of values (Fig. S1a and b) reveals their skewed nature owing to outliers that unduly influence the respective means and standard deviations. With the exception of a few, the outliers for both ice and snow are almost exclusively associated measurements on Icelandic or Spitzbergen ice caps or outlet glaciers, and on the Greenland Ice Sheet. In some instances, this might suggest the reduced role of local topography in limiting incoming solar radiation and/or other peculiarities of local energy balances [45]. (More modest values have also, however, been determined in these locations.) Given their skewness – especially that for m_f for ice, the appropriate descriptive statistics are the median and interquartile range (as a measure of dispersion). Accordingly for ice, the median m_f is 6.7 mm °C^{-1} d^{-1} with an interquartile range of 5.6 to 7.9 mm °C^{-1} d^{-1}. For snow, the median m_f is 4.0 mm °C^{-1} d^{-1} with an interquartile range of 3.2 to 4.6 mm °C^{-1} d^{-1}.

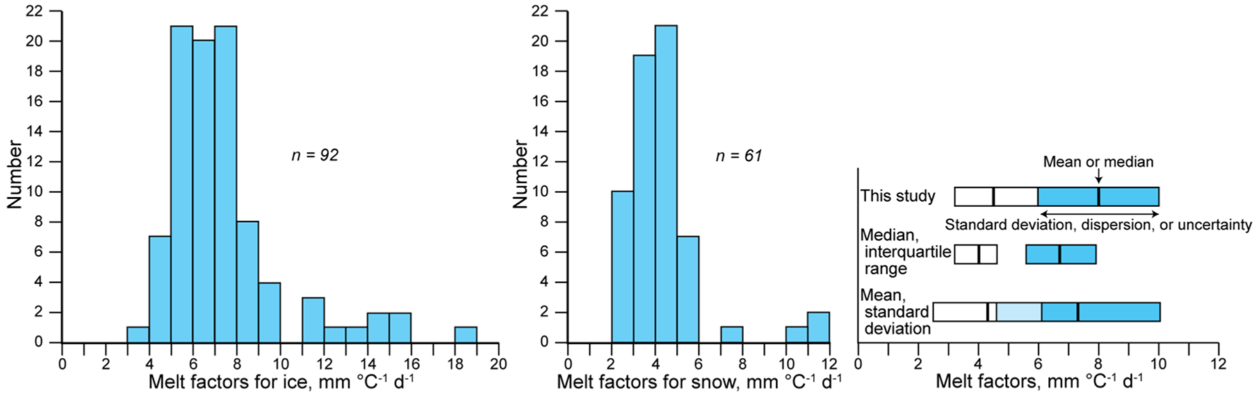

Figure S1. Distribution of published values of melt factor for (a) ice and (b) snow. (c) Statistical characteristics of distributions compared with assumed values used in the temperature-index model.

Our use of 8.0 ± 2.0 mm °C^{-1} d^{-1} for ice and 4.5 ± 2 mm °C^{-1} d^{-1} for snow in the modeling is thus guided by the foregoing, but *importantly* to also facilitate direct comparison with previous studies using the same melt factors in temperature index approaches to inferring temperature depression during the Last Glacial Maximum in Colorado [46-49]. Ultimately our assigned uncertainties in both melt factors (± 2.0 mm °C^{-1} d^{-1}) provide envelopes encompassing reasonable ranges in values (Fig S1c). Moreover, our means and standard deviations compare favorably with previous compilations [7,8,47,50], and those *assumed* in other modeling studies wherein glacier mass balance is required on various spatial scales (global to regional to individual catchments) and/or to understand present, past, and future behavior [e.g. 22, 51-55].

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