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Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data

Valentina Radić[1,2] and Regine Hock[2,3]

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[1] Very few global-scale ice volume estimates are available for mountain glaciers and ice caps, although such estimates are crucial for any attempts to project their contribution to sea level rise in the future. We present a statistical method for deriving regional and global ice volumes from regional glacier area distributions and volume area scaling using glacier area data from ~123,000 glaciers from a recently extended World Glacier Inventory. We compute glacier volumes and their sea level equivalent (SLE) for 19 glacierized regions containing all mountain glaciers and ice caps on Earth. On the basis of total glacierized area of $741 \times 10^3 \pm 68 \times 10^3$ km^2, we estimate a total ice volume of $241 \times 10^3 \pm 29 \times 10^3$ km^3, corresponding to 0.60 ± 0.07 m SLE, of which 32% is due to glaciers in Greenland and Antarctica apart from the ice sheets. However, our estimate is sensitive to assumptions on volume area scaling coefficients and glacier area distributions in the regions that are poorly inventoried, i.e., Antarctica, North America, Greenland, and Patagonia. This emphasizes the need for more volume observations, especially of large glaciers and a more complete World Glacier Inventory in order to reduce uncertainties and to arrive at firmer volume estimates for all mountain glaciers and ice caps.

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1. Introduction

[2] How much water is stored in the Earth's mountain glaciers and ice caps? This knowledge is crucial for projecting future sea level rise from the melt of glaciers and for determining the impacts of shrinking glaciers on terrestrial water resources. However, very few direct measurements exist, and estimates on a global scale are highly uncertain. Volumes of only a couple of hundred individual glaciers (fewer than 1% of the glaciers in the world) have been derived from field data such as ground penetrating radar and borehole measurements [e.g., *Bogorodsky et al.*, 1985; *Flowers and Clarke*, 1999]. More abundant are data on glacier surface areas. Estimates of total area of mountain glaciers and ice caps (including those in Greenland and Antarctica, but excluding the ice sheets) vary between 680×10^3 km^2 and 785×10^3 km^2 (Table 1). To date only ~40% of the area is inventoried in the World Glacier Inventory (WGI) and made available through the World Glacier Monitoring System [*World Glacier Monitoring Service* (*WGMS*), 1989] and the National Snow and Ice Data Center [*National Snow and Ice Data Center* (*NSIDC*), 1999], including data on the glacier's geographic location, length, orientation, elevation and morphological type. In order to extend the coverage of WGI, the Global Land Ice Measurements from Space (GLIMS) initiative was launched in 1995 to continue the inventorying task with spaceborne sensors [e.g., *Bishop et al.*, 2004] and to extend it by including glacier outlines. Although GLIMS has made substantial progress, its archive currently contains information on less than one third of the total glacierized area. Hence, both inventories are incomplete. *Cogley* [2009] recently compiled a more complete version of the WGI, called 'extended format' (WGI-XF), containing records for just over 131,000 glaciers, covering approximately half of the global mountain glacier and ice cap area. This WGI-XF came from assimilation of existing inventories including a number of older regional inventories that have been documented [*WGMS*, 1989] but not included in the WGI, and new inventories in Canada and the Sub-Antarctic.

[3] Glacier thickness and volume estimates have been made based on the principles of ice flow [e.g., *Haeberli and Hoelzle*, 1995; *Clarke et al.*, 2009; *Farinotti et al.*, 2009]. These methods, although powerful, are hampered in their application on global scale mostly due to paucity of required input data, such as detailed glacier topography. Therefore, the most common way to derive global-scale glacier volume is through volume-area scaling relation [e.g., *Meier and Bahr*, 1996; *Raper and Braithwaite*, 2005]. *Chen and Ohmura* [1990] derived a power law relation between glacier volume and area based on statistical regression of data from 63 mountain glaciers. This relation was further investigated by *Bahr* [1997a] and *Bahr et al.* [1997] who

[1]Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada.
[2]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[3]Department of Earth Sciences, Uppsala University, Uppsala, Sweden.

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Table 1. Total Areas and Volumes of Mountain Glaciers and Ice Caps Excluding and Including Those in Antarctica and Greenland[a]

Source	Area[b]		Volume[c]		Sea Level Equivalent (m)	
	Excluding	Including	Excluding	Including	Excluding	Including
Meier and Bahr [1996]	540	680	-	180 ± 4[d]	-	0.5 ± 0.1
Ohmura [2004]	521	-	51	-	~0.15	-
Dyurgerov and Meier [2005]	540 ± 30	785 ± 100	133 ± 20	260 ± 65	0.33 ± 0.05	0.65 ± 0.16
Raper and Braithwaite [2005]	522	-	87 ± 10[d]	-	0.241 ± 0.026	-
This study	518 ± 2	741 ± 68	166 ± 10	241 ± 29	0.41 ± 0.03	0.60 ± 0.07

[a]Sea level equivalent is calculated assuming oceanic area of 3.62×10^8 km^2 and a glacier density of 900 kg m^{-3}.
[b]Area values are $\times 10^3$ km^2.
[c]Volume values are $\times 10^3$ km^3.
[d]Volumes are given in water equivalent according to original reference, and not in ice equivalent as those of the other studies.

showed that the power law relation can be derived from dimensional analysis of glacier dynamics and glacier geometry. Due to the nonlinear character of the glacier volume-area relation it is not possible to derive regional or global ice volume only from the estimate of total glacierized area; additionally the glacier-area distribution of the glacier population is needed. *Meier and Bahr* [1996] and *Bahr and Meier* [2000] circumvented the problem of incomplete glacier inventories by using scaling methods to estimate the number and glacier-area distribution of glaciers in the world. For regions with complete glacier inventories, *Meier and Bahr* [1996] found distinct cumulative glacier-area distributions to which they fitted empirical functions with parameters determined for each region. These functions were then applied to regions with sparse glacier inventories requiring only knowledge of the approximate total glacierized area and the area of the largest glacier to assess the glacier-area distributions for each region. Total ice volume of all the mountain glaciers and ice caps (including those in Greenland and Antarctica) was estimated to be 0.5 ± 0.1 m sea level equivalent (SLE). Following the same methodology but using an updated glacier inventory, *Dyurgerov and Meier* [2005] derived 0.65 ± 0.16 m SLE, and 0.33 ± 0.05 m SLE when glaciers in Greenland and Antarctica are excluded (Table 1).

[4] *Raper and Braithwaite* [2005] suggested an alternative approach to estimate glacier-area distributions of incompletely inventoried regions. They plotted frequency distributions of glacier size for several regions, and related the slopes of log linear fits to the roughness of the regional topography. Using the gridded glacierized data for the globe at 1° × 1° resolution from *Cogley* [2003] and a global digital elevation model, they estimated the glacier-area distribution for each grid cell. Excluding glaciers in Greenland and Antarctica they derived lower estimates of SLE: 0.241 ± 0.026 m (Table 1). *Ohmura* [2004] compiled the somewhat rough estimates of regional ice volumes reported in different sources and derived a global SLE of 0.15 m, also excluding glaciers in Greenland and Antarctica (Table 1). However, it remains unclear how the estimates on regional volumes were derived considering that no or only few measurements of glacier thickness per region exist.

[5] In summary, very few global-scale ice volume estimates are available (Table 1), and these differ considerably between authors. Only two estimates include the mountain glaciers and ice caps in Greenland and Antarctica. In addition, except for *Ohmura* [2004] none of the authors report estimates of regional ice volume, although all studies compute these as an intermediate step to calculate global ice volume. The lack of regional volume estimates makes it difficult to identify the sources of their disagreements.

[6] In this paper we present an alternative way of deriving global ice volumes of mountain glaciers and ice caps from glacier-area distributions and scaling methods. We extract location and surface areas from glaciers available in the WGI-XF [*Cogley*, 2009] and compute their volumes using volume-area scaling [*Bahr et al.*, 1997]. For regions where the WGI-XF is incomplete, but total glacierized area of ice cover is known, we "upscale" the volume of the WGI-XF glaciers as a function of the portion of glaciers missing in WGI-XF and upscaled glacier-area distributions. Results are compiled for 19 geographical regions (Figure 1) including nearly all mountain glaciers and ice caps on Earth.

2. Data

2.1. Enlarged Version of the World Glacier Inventory

[7] WGI-XF contains information for just over 131,000 glaciers throughout the world [*Cogley*, 2009]. The core of WGI-XF is the WGI as available from the U.S. National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, which in turn consists of the WGI proper [*WGMS*, 1989] and the Eurasian Glacier Inventory [*Bedford and Haggerty*, 1996]. The inventory entries from NSIDC are based upon a single observation in time, where the average map year is 1964 with standard deviation of eleven years, and a time range from 1901 to 1993. Parameters needed for our methodology include geographic location and surface area, and we extract these data for all glaciers from WGI-XF with area ≥0.01 km^2, in total 122,804 glaciers. Since WGI-XF does not contain any glaciers in Iceland we add 16 Icelandic ice caps from the Icelandic Inventory provided by O. Sigurðsson (personal communication, 2008). We also supplement the data by adding 47 Alaskan mountain glaciers from data compiled by *Arendt et al.* [2002] that are not included in WGI-XF. Hence, we include 120,229 mountain glaciers and 2638 ice caps in our analysis, these data henceforth referred to as the WGI-XF data set.

2.2. Glacier Area

[8] According to WGI-XF 10 out of the 19 regions have a complete glacier inventory: Svalbard, Scandinavia, Central Europe, Franz Josef Land, Novaya Zemlya, Severnaya

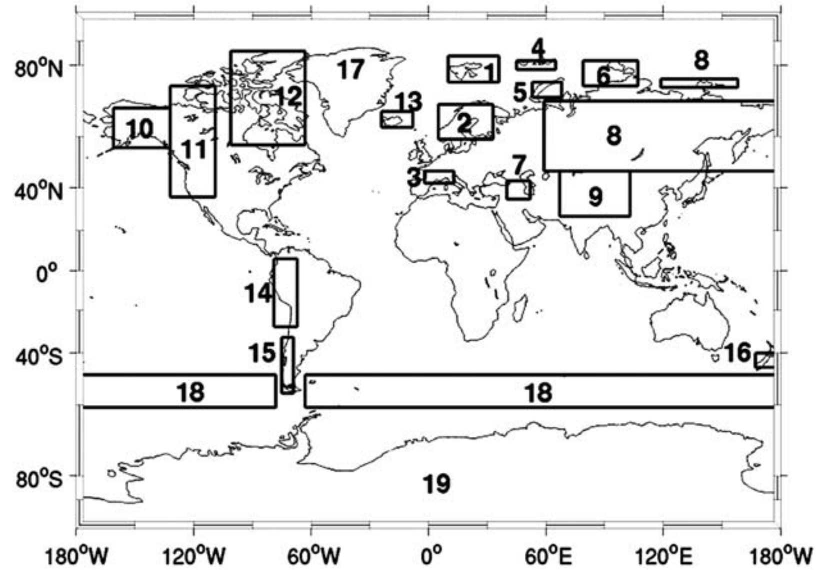

Figure 1. Location of the 19 regions for which regional glacier volumes are computed (Table 2). Note that region 12 does not include any glaciers in Greenland. Regions 17 (Greenland) and 19 (Antarctica) include all mountain glaciers and ice caps apart from the ice sheets.

Zemlya, Caucasus, North and East Asia, Iceland, and New Zealand. We note that the Icelandic inventory does not include mountain glaciers, but their total area is negligible compared with the total area of all Icelandic ice caps. We omit glaciers from northern Columbia, Venezuela, Mexico, Africa, and New Guinea, since their total glacierized area is less than 50 km^2, and also those on Jan Mayen (roughly 100 km^2).

[9] For the 10 regions with complete inventory we determine total glacierized area per region, A_{region}, from the WGI-XF data set. For the regions with incomplete glacier inventories we use the GGHYDRO 2.3 [*Cogley*, 2003] data set that gives the percentage of glacierization on a 1° × 1° global grid from which *de Woul* [2008] derived glacierized area per grid cell. For glaciers surrounding the Greenland ice sheet we use the data set by *de Woul* [2008] who resampled the data set of *Weng* [1995] to a 1° × 1° grid. For Antarctica, we follow *Dyurgerov and Meier* [2005] who adopted the area estimate by *Shumskiy* [1969] (169 × 10^3 km^2). *De Woul* [2008] and *Hock et al.* [2009] arrived at a lower value (132 × 10^3 ± 11 × 10^3 km^2), however, their estimate does not include the glaciers on the Antarctic mainland, and therefore represents a lower bound. The glacierized areas for each of our 19 regions, A_{region}, are listed in Table 2 together with the areas of WGI-XF glaciers alone, $A_{WGI\text{-}XF}$.

3. Methodology

3.1. Deriving Volume for All WGI-XF Glaciers

[10] We use volume-area scaling [e.g., *Erasov*, 1968; *Zhuravlev*, 1988; *Bahr et al.*, 1997; *Radić et al.*, 2007, 2008] to estimate the volumes of all WGI-XF glaciers:

$$V = cA^{\gamma}, \qquad (1)$$

where V and A are volume and surface area of a single glacier, while c and γ are scaling parameters. Estimates for γ and c are scarce. Based on theoretical considerations *Bahr* [1997b] for mountain glaciers derived γ = 1.375, while an analysis on 144 measured glaciers yielded γ = 1.36 [*Bahr et al.*, 1997]. Using the same data set, *Bahr* [1997b] derived c = 0.191 m$^{3-2\gamma}$, while *Chen and Ohmura* [1990] found c = 0.2055 m$^{3-2\gamma}$ for 63 mountain glaciers when adopting γ = 1.36. Here, we choose c = 0.2055 m$^{3-2\gamma}$ and γ = 1.375, but consider the uncertainties in scaling parameters in the error analysis (see section 4.2).

[11] For ice caps we assume a parabolic form of thickness-length relation assuming a constant basal shear stress [*Paterson*, 1994]:

$$H = 3.4L^{0.5}, \qquad (2)$$

where H is maximum thickness (at the center of the ice cap) and L is radius, both in meters. Considering an ice cap with a circular plan its area and volume are determined by

$$A = \pi L^2, \qquad (3)$$

$$V = \frac{2}{3}\pi H L^2, \qquad (4)$$

which can be expressed in terms of the volume-area relation (equation (1)) with c = 1.7026 m$^{3-2\gamma}$ and γ = 1.25.

3.2. Glacier Area Distributions of WGI-XF Glaciers

[12] For each region, glaciers from WGI-XF are distributed into size bins and the total area of WGI-XF glaciers per size bin, A_i, is determined (where i is the index of the bins). Similar to *Raper and Braithwaite* [2005] we assign the upper boundaries for each area size bin to be 2^n km^2 with n = −3 to 14, meaning that the smallest size bin contains glaciers of less than 0.125 km^2 while the largest size bin in the WGI-XF data set contains glaciers between 8,192 km^2 and 16,384

Table 2. Glacierized Area for All WGI-XF Glaciers and Total Glacierized Area for 19 Regions Defined by a Box With Coordinates for NW Corner and SE Corner[a]

	Region	Geographical Coordinates				Area (km^2)	
		NW Corner		SE Corner		$A_{WGI\text{-}XF}$	A_{region}
1	Svalbard	83°N	10°E	77°N	36°E	36,506 ± 364	36,506 ± 364
2	Scandinavia	71°N	5°E	60°N	33°E	3057 ± 18	3057 ± 18
3	Central Europe	48°N	2°W	43°N	13°E	3045 ± 17	3045 ± 17
4	Franz Josef Land	82°N	45°E	80°N	65°E	13,739 ± 141	13,739 ± 141
5	Novaya Zemlya	77°N	53°E	73°N	68°E	23,645 ± 1132	23,645 ± 1132
6	Severnaya Zemlya	82°N	79°E	76°N	107°E	19,397 ± 566	19,397 ± 566
7	Caucasus	44°N	40°E	36°N	52°E	1397 ± 10	1397 ± 10
8	North and East Asia[b]	72°N	59°E	48°N	179°E	2902 ± 14	2902 ± 14
9	High Mountain Asia	48°N	67°E	28°N	103°E	107,340 ± 229	114,330 ± 729
10	Alaska[c]	70°N	161°W	57°N	132°W	27,818 ± 518	79,260 ± 1076
11	W. Canada and W. U.S.	76°N	132°W	37°N	109°W	2061 ± 14	21,480 ± 420
12	Arctic Canada	84°N	101°W	58°N	63°W	24,709 ± 264	146,690 ± 1068
13	Iceland	71°N	24°W	64°N	8°W	11,005 ± 821	11,005 ± 821
14	South America I	7°N	79°W	27°S	67°W	2765 ± 9	7060 ± 137
15	South America II	32°S	75°W	55°S	69°W	17,884 ± 278	29,640 ± 663
16	New Zealand	39°S	167°E	45°S	177°E	1156 ± 13	1156 ± 13
17	Greenland	85°N	13°W	58°N	80°W	14,555 ± 129	54,400 ± 4400
18	Sub-Antarctic islands	49°S	0°W	60°S	0°E	1287 ± 23	3740 ± 129
19	Antarctica	60°S	0°W	85°S	0°E	3457 ± 54	169,000 ± 68,000
	Total					317,724 ± 1708	741,448 ± 68,186

[a]See Figure 1. For errors see section 4.2.
[b]Additional box: NW corner: 78°N 118°E; SE corner: 75°N 158°E.
[c]Including northwestern Canada.

km^2, and the maximum number of size bins is 18. The range in area and number of size bins varies strongly between regions (Table 3). Not all regional inventories include glaciers in the smallest size classes, most likely because inventories are often truncated at some (varying) minimum size.

[13] Due to the nonlinearity of the volume-area scaling relation it is crucial that the largest size bins are included in the glacier-area distributions. Therefore, for regions with incomplete inventory we compare the largest glacier area in the WGI-XF data set to the available estimates in the literature and find that the largest glacier is missing in WGI-XF in Alaska (Bering glacier, 3632 km^2) [*Beedle et al.*, 2008], Arctic Canada (Devon ice cap, 14,000 km^2) [*Dowdeswell and Hambrey*, 2002], and in Greenland (Flade Isblink, 7908 km^2) [*Weng,* 1995]. We add these glaciers to the regional glacier-area distributions (Table 3). For Antarctica we assume Alexander Island's ice cap to represent the largest glacier area (4068 km^2) based on the gridded data set by *de Woul* [2008].

3.3. Upscaling Glacier Area Distributions

[14] For the nine regions with incomplete glacier inventories we need to upscale the glacier-area distributions to match total glacierized area, A_{region}, before assessing regional ice volumes. Three regions (Antarctica, West Canada and western United States, and Arctic Canada) have less than 20% coverage in WGI-XF (Figure 2).

[15] We upscale the glacier-area distribution by adding glacier area to consecutive size bins. Size bins are numbered by index i starting from the size bin with the smallest glaciers ($A_1 < 2^n$ km^2 with $n = -3$). Since the mean glacier area per size bin increases by a factor 2, we upscale the glacier area per size bin so that the area added to consecutive size

Table 3. Statistics of Area Distribution of WGI-XF Glaciers for 19 Regions[a]

	Region	M	Mth Size Bin	
			Area Range (km^2)	Mean A (km^2)
1	Svalbard	15	1024–2048	1203
2	Scandinavia	10	32–64	43
3	Central Europe	11	64–128	78
4	Franz Josef Land	14	512–1024	728
5	Novaya Zemlya	18	8192–16,384	11,130
6	Severnaya Zemlya	17	4096–8192	4540
7	Caucasus	10	32–64	35
8	North and East Asia	10	32–64	39
9	High Mountain Asia	15	1024–2048	1056
10	Alaska	16 (16)	2048–4096 (2048–4096)	2615 (3632)
11	W. Canada and W. U.S.	11	64–128	75
12	Arctic Canada	14 (18)	512–1024 (8192–16,384)	722 (14,000)
13	Iceland	17	4096–8192	8086
14	South America I	9	16–32	17
15	South America II	15	1024–2048	1265
16	New Zealand	11	64–128	98
17	Greenland	14 (17)	512–1024 (4096–8192)	760 (7908)
18	Sub-Antarctic islands	11	64–128	95
19	Antarctica	13 (16)	256–512 (2048–4096)	364 (4068)

[a]M is the number of size bins assuming the first size bin's area $A < 2^{-3}$ km^2 (although not all inventories include glaciers in lowest size bins). Size bins are delimited by upper boundaries of 2^n km^2 with n ranging from −3 to maximum 14. For the Mth (largest) size bin the area range and arithmetic mean of all WGI-XF glaciers are given. Numbers in brackets refer to adjusted values used in this study for the four regions (Alaska, Arctic Canada, Greenland, Antarctica) where the largest glacier was missing in WGI-XF and therefore manually added to the distribution (see text).

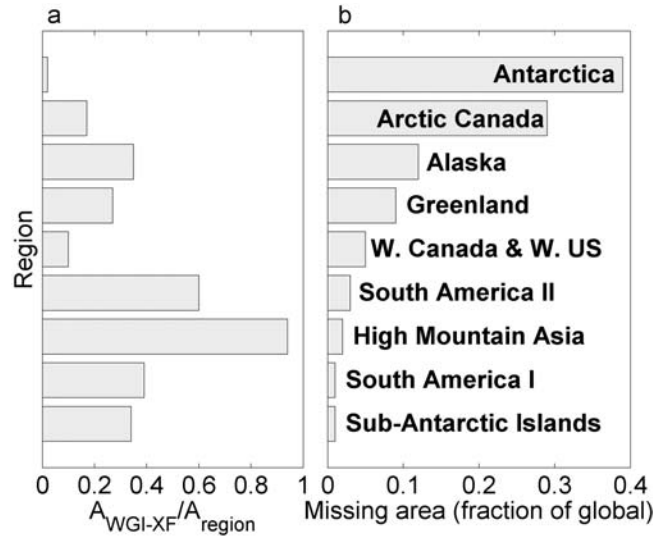

Figure 2. (a) Ratio between the area of WGI-XF glaciers, $A_{WGI\text{-}XF}$, and regional glacier area, A_{region}, for the nine glacierized regions that have incomplete glacier inventories. (b) Missing area in WGI-XF as a fraction of missing global glacierized area. While Figure 2a shows the degree of completeness of each regional inventory, Figure 2b indicates how much the different regions contribute to the global missing area.

bins also increases by a factor 2. This implies that an approximately equal number of glaciers is added to each size bin. For m consecutive size bins we compute glacier area according to

$$\begin{aligned} A_i' &= A_i + \frac{A_{region} - A_{WGI-XF}}{\sum_{n=0}^{m-1} 2^n} 2^{i-1} \\ &= A_i + \frac{A_{region} - A_{WGI-XF}}{2^m - 1} 2^{i-1}, i = 1, \cdots, m \end{aligned} \tag{5}$$

where A_i' is the upscaled area per size bin. The sum of the A_i' is equal to A_{region} for each region (Table 2). Upscaling always starts at $i = 1$; that is, glaciers are added to the smallest size bin, but upscaling is performed over fewer than the total number of size bins, M, i.e., $m < M$ (Table 3) for reasons explained below. We do not differentiate between mountain glaciers and ice caps when adding glacier area to the size bins.

3.4. Calculating Regional Ice Volumes

[16] For the 10 regions that have complete coverage in the WGI-XF we compute total ice volume directly from volume-area scaling. For the remaining nine regions, regional ice volume is obtained from upscaling the total WGI-XF glacier volume of each size bin, V_i:

$$V_i' = V_i \left(1 + \frac{A_i'}{A_i}\right), \tag{6}$$

where V_i' is the upscaled ice volume per size bin. Upscaling volume in this way we circumvent the problem of not knowing separately the number of mountain glaciers and ice caps that we have added to the size bin. These numbers would be needed if the total glacier volume was determined from volume-area scaling (equation (1)) of each individual glacier (as done for the WGI-XF glaciers), since scaling coefficients are different for mountain glaciers and ice caps.

[17] Regional glacier area distributions and resulting volumes depend on the choice of m in equation (5), i.e., the number of consecutive size bins over which the upscaling of area is performed. We investigate the sensitivity of the volume estimates to the choice of m by testing the upscaling method for six regions with complete inventories and sufficient numbers of glaciers to perform the tests (Svalbard, Scandinavia, Central Europe, Franz Josef Land, Caucasus, and New Zealand) before we apply the method on regions with incomplete inventories. We apply a Monte Carlo analysis of split sample tests. Glaciers from each of the six regions with a complete inventory are randomly sampled so that the samples contain 90% to 10% (decreasing by 10%) of the total number of glaciers in the region, thus simulating the cases of incomplete inventories. However, we do not allow each region's largest WGI-XF glacier to be removed from the inventory, since for each region with incomplete inventory the approximate area of the largest glacier is known. Hence, m (equation (5)) remains unaltered at this stage. In total we derive 100 area distributions for each of the nine sample sizes and upscale them using four choices for m (tests 1–4). Test 1 assumes that $m = M$ (Table 3), i.e., the upscaling is performed over all size bins including the largest bin. In test 2 we use $m = M - 1$, meaning that the size bin with the largest glacier is excluded from the upscaling, hence its area remains unaltered, while in test 3 and test 4 we use $m = M - 2$ and $m = M - 3$, respectively, meaning that the two (three) last size bins are excluded from the upscaling.

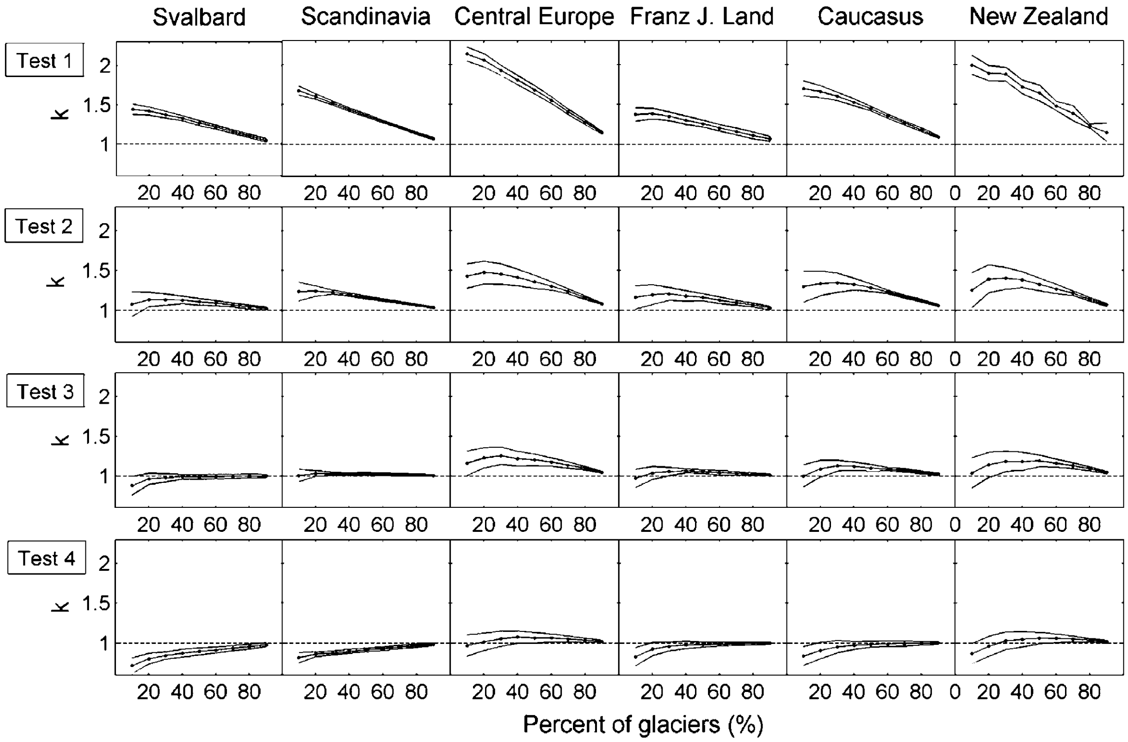

Figure 3. Ratio, k, of upscaled regional ice volume and the ice volume, V_{region}, obtained from the complete inventory (equation (7)) as a function of initial sample size derived by randomly removing glaciers from the complete inventory of six regions. Results are shown for four different tests of upscaling glacier-area distributions: Upscaling is performed over all the size bins ($m = M$, equation (5)) (test 1). The last size bin (largest glacier area) is excluded from the upscaling ($m = M - 1$) (test 2). The last two size bins are excluded from the upscaling ($m = M - 2$) (test 3). The last three size bins are excluded from the upscaling ($m = M - 3$) (test 4). Middle line is the mean value for k derived from 100 random samples of the WGI-XF glaciers, while the intervals correspond to the mean ± standard deviation.

[18] As a measure of the bias in upscaled volumes in tests 1–4 we define

$$k = \frac{V'_{region}}{V_{region}}, \tag{7}$$

where V'_{region} is the upscaled ice volume and V_{region} is volume obtained from volume-area scaling based on the complete inventory. In Figure 3, k is displayed for the six regions and tests 1 to 4 as a function of initial sample size. For most cases in tests 1 to 3, k is larger than 1, meaning that the upscaling method overestimates the regional ice volumes. The largest overestimation is for test 1, for all six regions, while test 3 provides the closest match between the upscaled volume and original regional volume. Test 4 tends to slightly underestimate glacier volume although, the "sign" of the bias is less consistent. As expected, the uncertainty range (standard deviation) of k increases with decreasing sample size, meaning that the biases in the upscaled volume estimates are larger if the inventory is poorer. Test 1 indicates that, in particular for poor inventory coverage, upscaling over all size classes ($m = M$) according to equation (5) leads to unrealistic results most likely because too many large glaciers are added.

[19] Based on these experiments, for the nine regions with incomplete inventories we upscale the area distribution according to test 3, assuming $m = M - 2$ (equation (5) and Table 3), and compute regional volume from equation (6). Results are shown in Figures 4 and 5. We then assume that the resulting regional volume estimates have the same bias for identical degree of inventory incompleteness as obtained on average over all six regions from test 3. Hence, we apply a bias correction by dividing the regional volume estimates by the mean k value (equation (7)) that corresponds to the region's degree of inventory incompleteness in the WGI-XF data set. The bias correction factors $1/k$ vary between 0.91 and 0.99 (Table 4). Potential SLE is calculated by converting total ice volume into water equivalent (assuming density of ice 900 kg m^{-3}) and dividing by the oceanic area of 3.62×10^8 km^2.

4. Results and Discussion

4.1. Potential Sea Level Equivalent

[20] Table 4 contains our regionally differentiated ice volume and corresponding SLE estimates for 19 regions. When summed over all regions, SLE amounts to 0.60 ± 0.07 m, while the WGI-XF glaciers alone contain 0.17 ± 0.01 m SLE. Global mean ice thickness is 326 m. Excluding the glaciers in Greenland and Antarctica the total SLE is equal to 0.41 ± 0.03 m, while all the glaciers surrounding the ice sheets contribute 0.19 ± 0.06 m, or 32% of the global

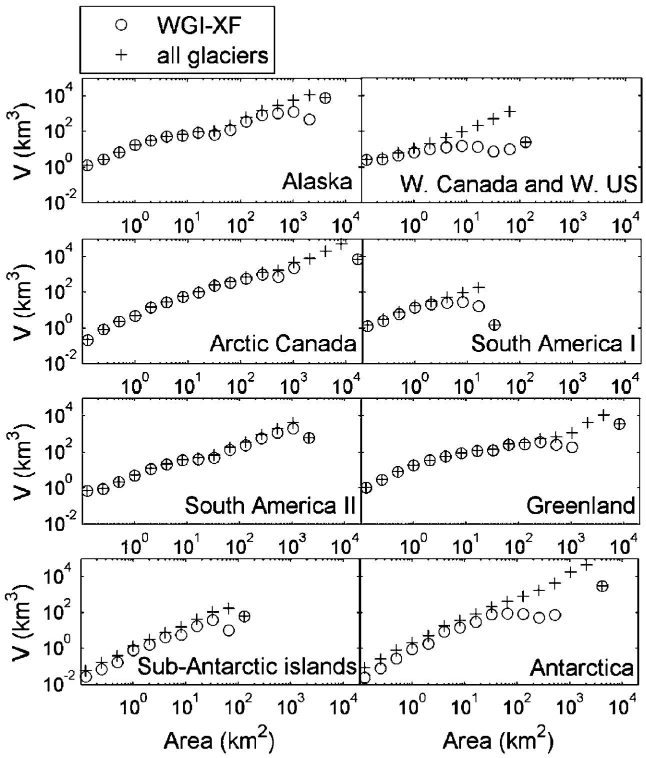

Figure 4. Volume, V, per size bin for the WGI-XF glaciers (circles) and for all glaciers as estimated from upscaling (equations (5) and (6), crosses) using $m = M - 2$ shown for eight regions. Labels denote upper boundaries of the size bins.

SLE. The mountain glaciers and ice caps in Antarctica alone contribute 25% to global SLE.

[21] Our global estimate is slightly smaller than the previous estimate of *Dyurgerov and Meier* [2005]. However, their estimate includes a larger relative contribution (51%) from the glaciers in Greenland and Antarctica (Table 1). Our SLE estimate for all glaciers outside Greenland and Antarctica is 70% larger than the estimate of *Raper and Braithwaite* [2005] and almost threefold the estimate of *Ohmura* [2004] (Table 1). Differences are attributed to a combination of different methodologies and different input data, and emphasize the uncertainties arising from unknown glacier-area distributions in many regions with large ice covers such as Antarctica, Arctic Canada, Alaska, Greenland and Patagonia.

[22] Our methodology elaborates on approaches by *Meier and Bahr* [1996] and *Raper and Braithwaite* [2005] yet differs in several aspects. We compute volumes of ~123,000 WGI-XF glaciers directly based on volume-area scaling. These glaciers account for roughly half of global glacierized area. We circumvent the need to know the number of both mountain glaciers and ice caps per region by upscaling glacier volumes as a function of glacierized area missing in the WGI-XF, instead of computing volumes from volume-area scaling of the total number of glaciers, as done in previous studies [*Meier and Bahr*, 1996; *Raper and Braithwaite*, 2005]. We also avoid the problem of treating glaciers on a spatial grid [*Meier et al.*, 2005] by upscaling glacier volumes on regional scales instead of grid cell scales.

[23] Figure 6 shows the contribution of each region to global SLE compared to each region's contribution to global glacierized area. The five regions with the largest SLE are Canadian Arctic, Antarctica, Alaska, Greenland, and High Mountain Asia. However, the ranking of the five regions with the largest ice covered areas is different: Antarctica, Canadian Arctic, High Mountain Asia, Alaska, and Greenland. This indicates that a region containing fewer glaciers, of which most are large, has more SLE than a region with many smaller glaciers. This difference is due to the power law nature of the volume-area relation.

4.2. Uncertainties

[24] Error estimates (Table 4) are derived following the principle of error propagation for the function of N variables $f(X_1,\ldots,X_N)$ [e.g., *Bevington*, 1969]:

$$(\delta f)^2 = \sum_{j=1}^{N} \left(\frac{\partial f}{\partial X_j}\right)^2_{\overline{X_j}} (\delta \overline{X_j})^2, \qquad (8)$$

where δX_j are independent and random errors of the variables X_j.

[25] We propagate the errors in glacier area and scaling coefficients γ and c (equation (1)), which are assumed to be independent, to obtain the errors of volume for each individual glacier and of all WGI-XF glaciers per region, $V_{WGI\text{-}XF}$. Since the measurement error for glacier area is generally not reported in WGI-XF, we assume it to be 10% for each individual glacier. This error partly accounts for the large time range of the area measurements. However, due to lack of information, we do not account for errors occurring for glaciers whose area significantly changed since measured and reported in WGI-XF. Smaller areas tend to have greater uncertainties (J. G. Cogley, personal communication, 2009), but it would not be justified to allow for this little-known effect at this scale of analysis. The error in the scaling exponent γ is assumed to equal the difference between $\gamma = 1.36$ and $\gamma = 1.375$ derived by *Bahr et al.* [1997] and *Bahr* [1997b], respectively. In the work of *Bahr* [1997b] the standard deviation of the probability density function for c is approximately 40% of the mean of the distribution. Therefore the error in scaling constant c is assumed 40% of c.

[26] To quantify the error in V_{region} we include the results from the sensitivity tests (tests 1 to 4). There are three variables whose uncertainties propagate in the upscaling of the glacier-area distribution: $V_{WGI\text{-}XF}$, $A_{WGI\text{-}XF}$ and A_{region}. However, errors in $V_{WGI\text{-}XF}$ and $A_{WGI\text{-}XF}$ are not independent and therefore the standard error propagation (equation (8)) is not applicable. Errors for A_{region} are derived by propagating the errors for each 1° × 1° glacierized grid cell [*de Woul*, 2008], assuming the error for each grid cell to be 8% of total ice area in the grid cell. Since for each region with incomplete inventory the error in A_{region} is larger than the error in $A_{WGI\text{-}XF}$, we upscale the glacier-area distribution ($m = M - 2$, equation (5)) to match the upper and lower bound for A_{region}, i.e., A_{region} ± error. This provides the uncertainty in the upscaled volume, V_{region}, due solely to the error in total glacierized area. However, since the number of glaciers missing in each size bin is unknown, we introduce an error

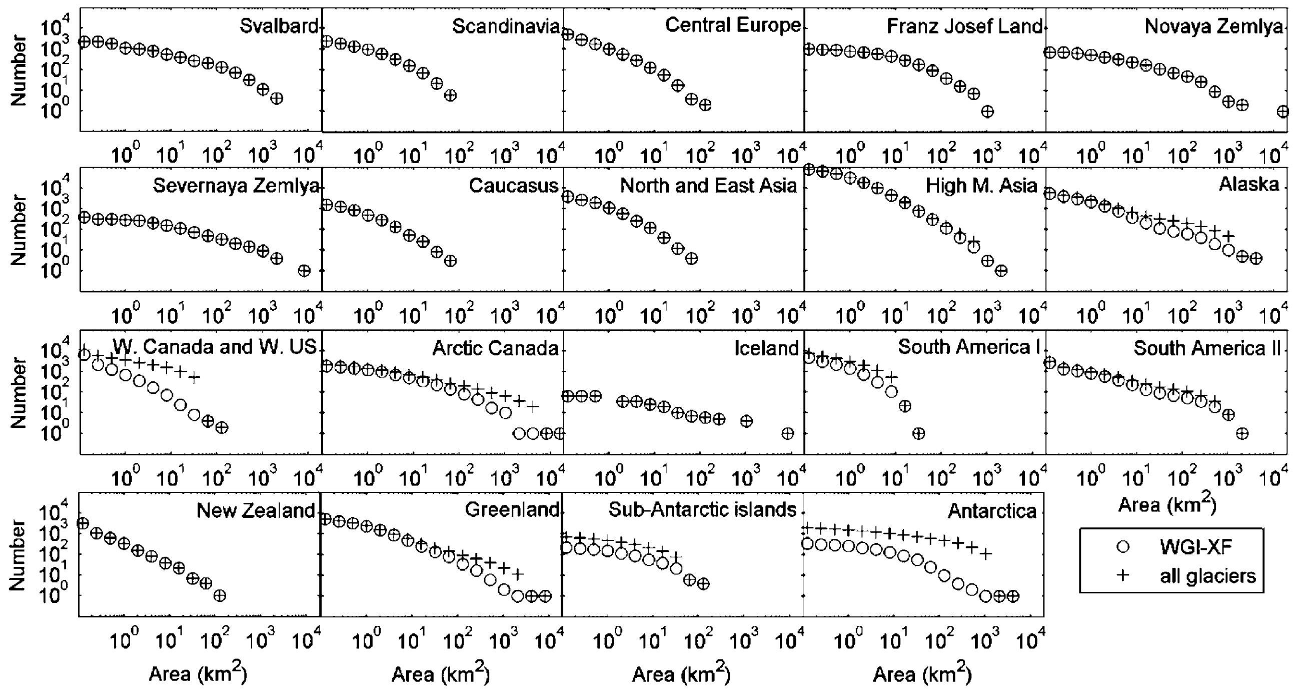

Figure 5. Cumulative number of glaciers with areas larger than a given area for the WGI-XF glaciers (circles) and all glaciers as computed by our upscaling method (crosses) using $m = M - 2$ (equation (5)) for nine regions. The regions with overlapping circles and crosses have complete glacier inventory and the upscaling is not performed. Labels denote upper boundaries of the size bins.

with our arbitrary choice to upscale area size distribution by adding area per size bin that increases with a multiplication factor 2 (equation (5)). This systematic error is partially quantified by the ratio k (equation (7)), derived as a mean value over the six regions with complete inventories. We choose the maximum standard deviation of k over six regions, to represent an uncertainty of k depending on the percentage of inventory coverage in the region. Both errors, in k and in V_{region}, are then propagated to derive the error in the final estimate of V_{region} and in global ice volume, V_{global}. We note that all the errors propagated in the final estimates are assumed to be standard errors of normally distributed sample, and represent the uncertainty interval with 68% confidence level.

[27] In addition, we perform experiments to assess the sensitivity of volume estimates to the choice of various parameters. We derive bias corrected V_{region} and V_{global} using k values derived from test 2 ($m = M - 1$, equation (5))

Table 4. Volume Estimates for the WGI-XF Glaciers and All Glaciers for 19 Regions

	Region	$V_{WGI\text{-}XF}$ (km^3)	V_{region} (km^3)	$\mathrm{SLE}_{\mathrm{region}}$ (mm)	$1/k$[a]
1	Svalbard	10,260 ± 823	10,260 ± 823	26 ± 2	-
2	Scandinavia	224 ± 11	224 ± 11	0.56 ± 0.03	-
3	Central Europe	194 ± 12	194 ± 12	0.48 ± 0.03	-
4	Franz Josef Land	2248 ± 176	2248 ± 176	5.6 ± 0.4	-
5	Novaya Zemlya	9410 ± 3388	9410 ± 3388	23 ± 8	-
6	Severnaya Zemlya	6046 ± 1231	6046 ± 1231	15 ± 3	-
7	Caucasus	88 ± 6	88 ± 6	0.22 ± 0.01	-
8	North and East Asia	170 ± 8	170 ± 8	0.42 ± 0.02	-
9	High Mountain Asia	10,877 ± 404	12,483 ± 462	31 ± 1	0.98 ± 0.02
10	Alaska	10,477 ± 1816	27,436 ± 3312	68 ± 8	0.91 ± 0.10
11	W. Canada and W. U.S.	124 ± 11	1892 ± 361	4.7 ± 0.9	0.99 ± 0.19
12	Arctic Canada	6102 ± 510	80,160 ± 12,151	199 ± 30	0.92 ± 0.14
13	Iceland	4889 ± 2244	4889 ± 2244	12 ± 6	-
14	South America I	131 ± 3	344 ± 37	0.86 ± 0.09	0.91 ± 0.10
15	South America II	5532 ± 633	8116 ± 712	20 ± 2	0.93 ± 0.05
16	New Zealand	83 ± 11	83 ± 11	0.21 ± 0.03	-
17	Greenland	1981 ± 153	17,865 ± 2993	44 ± 7	0.91 ± 0.11
18	Sub-Antarctic islands	159 ± 19	363 ± 44	0.9 ± 0.1	0.91 ± 0.11
19	Antarctica	487 ± 55	59,158 ± 25,829	147 ± 64	0.99 ± 0.19
	Global	69,481 ± 4784	241,430 ± 29,229	600 ± 73	

[a] $1/k$ refers to the bias correction factor in test 3 by which regional volume estimates derived from Equations 5 and 6 for the 9 regions with incomplete WGI-XF inventories have been multiplied to obtain the final volume estimates, V_{region} (see text).

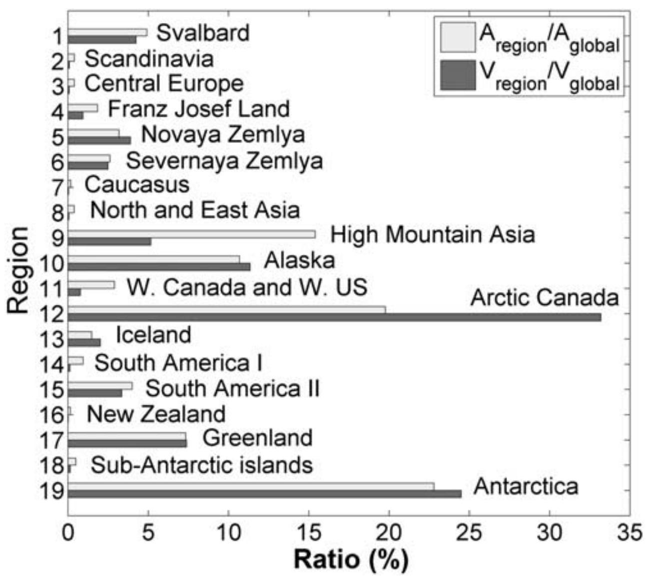

Figure 6. Percentage of ice-covered area and volume of 19 regions, A_{region} and V_{region}, to global glacierized area and volume, A_{global} and V_{global}, respectively.

resulting in global SLE of 0.63 ± 0.07 m. When test 4 is used the resulting global SLE is 0.53 ± 0.08 m. These results are within the uncertainty range of the original SLE. To address the uncertainty in the number of mountain glaciers versus ice caps we perform a sensitivity experiment where all WGI-XF glaciers are assumed to scale according to the mountain glacier scaling coefficients (γ, c, equation (1)). SLE from the WGI-XF glaciers increases from the original estimate of 0.17 m to 0.22 m. The upscaled global SLE increases from 0.60 m to 0.69 m. This increase is to be expected since the scaling exponent γ for a mountain glacier is larger than that for an ice cap. Vice versa, considering all ice masses to be ice caps, SLE from the WGI-XF glaciers decreases to 0.15 m, while the upscaled global SLE decreases to 0.55 m.

[28] Another uncertainty arises from the assumption on area estimate of the largest glacier per region which is required input to our upscaling methodology. Reported area estimates for large glaciers may differ considerably due to different interpretations as to the boundary of the glacier. Large glaciers are often part of complex glacier systems aggregated from multiple drainage basins, numerous tributaries and many accumulation areas, and definition of boundaries is not straightforward. For example, *Molnia and Post* [1995] list Bering Glacier as the largest glacier in Alaska/northwestern Canada with 5173 km^2 followed by Malaspina Glacier with 5000 km^2. This is considerably larger than *Beedle et al.*'s [2008] estimates (3632 km^2 and 3220 km^2, respectively), which we adopted here. As a sensitivity analysis we use 5000 km^2 for the largest glacier area in Alaska/northwestern Canada. This results in regional contribution of 0.011 m to global SLE, increasing global SLE by 2% (0.61 ± 0.07 m).

[29] Other uncertainties, which we do not investigate further here, are due to the choice of defining the glacierized regions over which the scaling is performed. Nevertheless, full validation of our results will only be possible once the glacier inventory is completed.

5. Conclusions

[30] We implement a regionally differentiated method by which total volume of mountain glaciers and ice caps on Earth can be estimated from glacier-area distributions and volume-area scaling. Our estimates are based on all available glacier areas from the recently extended World Glacier Inventory, WGI-XF, and on a global grid of glacierized area. The method requires at least partial coverage by inventory data including the largest glacier for defined subregions, and therefore it is not applicable in regions completely devoid of glacier-area distribution data.

[31] For total glacierized area of $741 \times 10^3 \pm 68 \times 10^3$ km^2 our upscaling algorithm estimates a total ice volume of $241 \times 10^3 \pm 29 \times 10^3$ km^3, corresponding to 0.60 ± 0.07 m SLE. The glaciers in Greenland and Antarctica alone contribute 32% to global SLE, and hence should be included in any attempts to predict the contribution of mountain glaciers and ice caps to future sea level rise.

[32] Results are sensitive to the assumptions on glacier-area distribution which poses a problem especially in areas with low inventory coverage. We emphasize a need for more comprehensive coverage of the World Glacier Inventory, especially in large ice volume regions such as Arctic Canada, Antarctica, Alaska and Greenland, to reduce uncertainties associated with upscaling glacier-area distributions. These four regions alone make up almost 90% of the area that is missing in the global WGI-XF inventory (Figure 2b). In particular, regional inventories need to include the large ice masses. Due to the nonlinearity of volume-area scaling relation lack of the largest size bin(s) in the glacier-area distribution has a much larger impact on total volume compared to the cases where smaller size bins are missing.

[33] Another source of uncertainty pertains to the choice of scaling coefficients in volume-area relation. More direct ice volume measurements are needed to constrain the scaling parameters especially for larger glaciers. Nevertheless our results provide a first-order approximation for global and regional glacier volumes as a foundation upon which to base projections of the contribution of mountain glaciers and ice caps to future sea level rise.

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References

Arendt, A. A., K. A. Echelmeyer, W. D. Harrison, S. C. Lingle, and V. B. Valentine (2002), Rapid wastage of Alaska glaciers and their contribution to rising sea level, *Science*, *297*, 382–386, doi:10.1126/science.1072497.

Bahr, D. B. (1997a), Width and length scaling of glaciers, *J. Glaciol.*, *43*, 557–562.

Bahr, D. B. (1997b), Global distributions of glacier properties: A stochastic scaling paradigm, *Water Resour. Res.*, *33*(7), 1669–1679, doi:10.1029/97WR00824.

Bahr, D. B., and M. F. Meier (2000), Snow patch and glacier size distributions, *Water Resour. Res.*, 36(2), 495–501, doi:10.1029/1999WR900319.
Bahr, D. B., M. F. Meier, and S. D. Peckham (1997), The physical basis of glacier volume-area scaling, *J. Geophys. Res.*, *102*(B9), 20,355–20,362, doi:10.1029/97JB01696.
Bedford, D., and C. Haggerty (1996), New digitized glacier inventory for the former Soviet Union and China, *Earth Syst. Monit.*, *6*(3), 8–10.
Beedle, M. J., M. Dyurgerov, W. Tangborn, S. J. S. Khalsa, C. Helm, B. Raup, R. Armstrong, and R. G. Barry (2008), Improving estimation of glacier volume change: A GLIMS case study of Bering Glacier System, Alaska, *The Cryosphere*, *2*, 33–51.
Bevington, P. R. (1969), *Data Reduction and Error Analysis for the Physical Sciences*, McGraw-Hill, New York.
Bishop, M. P., et al. (2004), Global Land Ice Measurements from Space (GLIMS): Remote sensing and GIS investigations of the Earth's cryosphere, *Geocarto Int.*, *19*(2), 57–84, doi:10.1080/10106040408542307.
Bogorodsky, V. V., C. R. Bentley, and P. E. Gudmandsen (1985), *Radioglaciology*, D. Reidel, Dordrecht, Netherlands.
Chen, J., and A. Ohmura (1990), Estimation of Alpine glacier water resources and their change since the 1870s, *IAHS Publ.*, *193*, 127–135.
Clarke, G. K. C., E. Berthier, C. G. Schoof, and A. H. Jarosch (2009), Neural networks applied to estimating subglacial topography and glacier volume, *J. Clim.*, 22(8), 2146–2160, doi:10.1175/2008JCLI2572.1.
Cogley, J. G. (2003), GGHYDRO - Global Hydrographic Data, Release 2.3, *Trent Tech. Note, 2003-1*, Dep. of Geogr., Trent Univ., Peterborough, Ont.
Cogley, J. G. (2009), A more complete version of the World Glacier Inventory, *Ann. Glaciol.*, *50*, 32–38.
de Woul, M. (2008), Response of glaciers to climate change: Mass balance sensitivity, sea level rise and runoff, Ph.D. thesis, Stockholm Univ., Stockholm.
Dowdeswell, J. A., and M. J. Hambrey (2002), *Islands of the Arctic*, 280 pp., Cambridge Univ. Press, Cambridge, U. K.
Dyurgerov, M. B., and M. F. Meier (2005), Glaciers and the changing Earth system: A 2004 snapshot, *Occasional Pap.*, *58*, 117 pp., Inst. of Arctic and Alpine Res. Univ. of Colo. at Boulder, Boulder, Colo.
Erasov, N. V. (1968), Method to determine the volume of mountain glaciers (in Russian), *Mater. Glyatsiol. Issled. Khronika. Obsuzhdniya*, 14, 307–308.
Farinotti, D., M. Huss, A. Bauder, M. Funk, and M. Truffer (2009), A method to estimate ice volume and ice-thickness distribution of alpine glaciers, *J. Glaciol.*, *55*, 422–430.
Flowers, G. E., and G. K. C. Clarke (1999), Surface and bed topography of Trapridge Glacier, Yukon Territory, Canada: Digital elevation models and derived hydraulic geometry, *J. Glaciol.*, *45*, 165–174.
Haeberli, W., and M. Hoelzle (1995), Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: A pilot study with the European Alps, *Ann. Glaciol.*, *21*, 206–212.
Hock, R., M. de Woul, V. Radić, and M. Dyurgerov (2009), Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution, *Geophys. Res. Lett.*, *36*, L07501, doi:10.1029/2008GL037020.
Meier, M. F., and D. B. Bahr (1996), Counting glaciers: Use of scaling methods to estimate the number and size distribution of the glaciers in the world, *CRREL Spec. Rep., 96–27*, U. S. Army, Hanover, N. H.
Meier, M. F., D. B. Bahr, M. B. Dyurgerov, and W. T. Pfeffer (2005), Comment on "The potential for sea level rise: New estimates from glacier and ice cap area and volume distribution" by S. C. B. Raper and R. J. Braithwaite, *Geophys. Res. Lett.*, *32*, L17501, doi:10.1029/2005GL023319.
Molnia, B. F., and A. Post (1995), Holocene history of Bering Glacier, Alaska: A prelude to the 1993–1994 surge, *Phys. Geogr.*, *16*(2), 87–117.
National Snow and Ice Data Center (NSIDC) (1999), World glacier inventory, http://nsidc.org/data/glacier_inventory/index.html, Boulder, Colo. (Updated 2007.)
Ohmura, A. (2004), Cryosphere during the twentieth century, in *The State of the Planet: Frontiers and Challenges in Geophysics*, *Geophys. Monogr. Ser.*, vol. 150, edited by R. S. J. Sparks and C. J. Hawkesworth, pp. 239–257, AGU, Washington, D. C.
Paterson, W. S. B. (1994), *The Physics of Glaciers*, 3rd ed., Pergamon, Oxford, U. K.
Radić, V., R. Hock, and J. Oerlemans (2007), Volume-area scaling vs flowline modelling in glacier volume projections, *Ann. Glaciol.*, *46*, 234–240, doi:10.3189/172756407782871288.
Radić, V., R. Hock, and J. Oerlemans (2008), Analysis of scaling methods in deriving future volume evolutions of valley glaciers, *J. Glaciol.*, *54*, 601–612, doi:10.3189/002214308786570809.
Raper, S. C. B., and R. J. Braithwaite (2005), The potential for sea level rise: New estimates from glacier and ice cap area and volume distributions, *Geophys. Res. Lett.*, *32*, L05502, doi:10.1029/2004GL021981.
Shumskiy, P. A. (1969), Glaciation, in Atlas of Antarctica, vol. 2, edited by E. Tolstikov, pp. 367–400, Hydrometeoizdat, Leningrad.
Weng, W. L. (1995), *Untitled, Arctic*, *48*(2), 206.
World Glacier Monitoring Service (WGMS) (1989), World glacier inventory: Status 1988, edited by W. Haeberli et al., IAHS(ICSI)/UNEP/UNESCO, World Glacier Monit. Serv., Zürich.
Zhuravlev, A. V. (1988) The relation between glacier area and volume, in *Data of Glaciological Studies*, vol. 40, edited by G. A. Avsyuk, *Russ. Transl. Ser.*, vol. 67, pp. 441–446, A. A. Balkema, Rotterdam, Netherlands.

R. Hock and V. Radić, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada.