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An estimate of global glacier volume

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Abstract

I asses the feasibility of multi-variate scaling relationships to estimate glacier volume from glacier inventory data. I calibrate scaling laws against volume observations of optimized towards the purpose of estimating the total global ice volume. This is applied individually to each record in the Randolph Glacier Inventory which is the first globally complete inventory of glaciers and ice caps. I estimate that the total volume of all glaciers in the world is 0.35 ± 0.07 m sea level equivalent. This is substantially less than a recent state-of-the-art estimate. Area volume scaling bias issues for large ice masses, and incomplete inventory data are offered as explanations for the difference.

1 Introduction

Globally glaciers are shrinking and are contributing to global sea level rise (Leclercq et al., 2011). Their potential contribution to sea level rise is limited by their total volume. Regional sea level rise will depend strongly on the spatial pattern of ice mass loss (Mitrovica and Milne, 2003; Slangen et al., 2011). Further, the glaciers are an important water resource in many regions. It is thus of great importance to estimate the volume of glaciers worldwide. It is presently not viable to measure the thickness and volume of all the remote glaciers on earth, and glacier volumes for the vast majority of glaciers have therefore been estimated from empirical (but physically reasonable) scaling laws between volume area (Bahr et al., 1997). An additional complication has been that there has not been any globally complete glacier inventory and previous estimates have relied on upscaling of incomplete inventories (e.g. Radić and Hock, 2010). This has led to a wide range of estimates which is reviewed in Cogley (2012). The IPCC TAR estimate of ~50 cm sea level equivalent (SLE) (Church et al., 2001) was revised to about 30 cm SLE in the IPCC AR4 (Lemke et al., 2007; Cogley, 2012). Radić and Hock (2010) have since estimated a volume of about 60 cm SLE.

In this paper, I revisit the scaling laws used to estimate volume for individual glaciers, and apply them to the new globally complete Randolph Glacier Inventory (RGI; Arendt et al., 2012).

2 Data

The three large global glacier inventories were used in this study: the World Glacier Inventory (WGI) which has extensive metadata on 132 000 glaciers and ice caps (WGMS and NSIDC). I also use the Global Land Ice Monitoring from Space (GLIMS) database which has glacier outlines and some metadata for 96 000 glaciers and ice caps (Armstrong et al., 2012). Finally I use the newly compiled Randolph Glacier Inventory v2 (RGI) which contains primarily 170 000 glacier outlines but not much additional metadata for each record. A series of semi-automated checks were applied to the inventory data to remove or correct for obvious reporting mistakes such as swapped maximum and minimum elevations or double reported polygons. Outlet glaciers from the Greenland ice sheet were removed from WGI. The spatial coverage of the databases is shown in Fig. 1. I adopt the regions defined by Arendt et al. (2012) which resembles those used by Radić and Hock (2010) but with some slight differences.

I augment RGI with additional data from GLIMS and WGI where it is possible to match records directly based on ids. Unfortunately only 23 % of the GLIMS records, and only 1 % of the WGI records can be matched with RGI glaciers in this manner. In order to take advantage of the rich metadata in WGI, I therefore also construct another global inventory where I start from WGI data, and then add GLIMS and RGI data successively. In order to avoid duplicates I exclude records based on matched id numbers, and secondly based on a distance filter. Both glacier databases end up with having ~ 170 000 records globally. Unfortunately, it is evident from comparing the regional areas between the two databases that there are remaining deficiencies to be resolved with this WGI/GLIMS database (Table 1). For example the two largest ice masses in Svalbard were excluded by the distance filtering.

I do not use WGI thickness data, as a high fraction of the reported values are the result of area-volume scaling laws, and therefore cannot be used to calibrate scaling laws. Cogley (2012) compiled a database of available observations of glacier volume estimates where thickness has been measured. In this paper I use an updated version of this database containing area, volume and elevation range of 210 glaciers and 34 ice caps (see Figs. 1, 2). This information is matched to inventory records where possible, but all volume records are retained for calibrating volume scaling laws.

For GLIMS and RGI I estimate the elevation range spanned by each glacier using the global digital elevation model (DEM) from the shuttle radar topography mission (SRTMv4; Jarvis et al., 2008) in 250 m resolution, and GTOPO30 as a fallback for high latitudes (Verdin and Greenlee, 1996). These DEM based elevation range estimates were found to be more reliable than those manually reported in GLIMS where. Nevertheless the DEM based range estimates does contain some errors due to misalignment errors between the coordinate systems used by the DEM and the reported glacier outlines. This misalignment will usually still result in reasonable range estimates, except for islands where misalignment can lead to extremely small range estimates. I therefore exclude range estimates below a 5 m threshold.

I will also use a global grid of continentality, determined ERA40 2 m temperatures. I here define the continentality as the standard deviation of the mean annual cycle (in monthly resolution).

3 Methods

The size of individual glaciers is quantified using many different metrics such as length (L), width (W), area (A), volume (V), elevation range (R), and average thickness (D). These quantities are generally correlated so that a large glacier in terms of area is also a large glacier in terms of volume. This has been used to establish scaling relationships between individual size measures such as volume and area. These scaling relationships usually take the form $V = k \cdot A^n$ or $\log(V) = \log(k) + n \cdot \log(A)$. This has been the only practical method available to estimate the total volume of all glaciers in the world is to use such volume scaling laws. Such scaling laws can be physically justified for idealized perfectly plastic glaciers where exponents, n of 1.375 and 1.25 have been argued to be appropriate for straight valley glaciers and circular ice caps respectively (Bahr et al., 1997). These relationships are designed to capture how the volume of an idealized glacier changes as it grows or shrinks. Of course these idealized assumptions are only approximations, and for real glaciers other exponents may give a more accurate approximation to their behavior. Further, there is no a priori reason to expect that the same scaling constant will be appropriate for all glaciers even if the idealized assumptions were to hold. That would imply a globally applicable yield stress, and thus all mountains to have roughly the same slope (Cuffey and Paterson, 2010). However, empirical estimates of volume and area support the notion that a near universal scaling law can be applied across a very wide range of sizes, although the scatter indicates (Fig. 2) that applying such scaling laws to individual glaciers can only provide estimates with large uncertainties in the range of 50–200 % (Moore et al., 2012).

The traditional technique to estimate the scaling law parameters (n and k) is least squares regression in a log-log space. The model arising from this approach is optimized to minimize the relative misfit for a very wide range of size classes and is heavily biased towards the small and medium sized glaciers for which most observations are available. Alternatively we can construct a model where the volume misfit is minimized. The scaling laws arising from such an approach is much better suited for sea level rise studies, as an error in the volume of a large ice mass is much more important than an error in a small ice mass. Robust minimum absolute deviation gives less importance to individual outliers compared to least squares, and will produce the best total volume estimates. I also calibrate using least squares volume misfit, but consider this to be a very fragile approach, as this will give extreme weight to the largest volume. A further improvement would be to introduce weighing to account for sampling bias in the calibration data set versus the full inventory.

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Ice caps may have different scaling relationship compared to glaciers. I therefore calibrate scaling laws separately for glaciers and ice caps. Unfortunately not all inventory records have been classified. Here I simply assign all unclassified glacier records with an area greater than 25 km^2 as being "ice caps". As the entire RGI inventory lacks this classification, the scaling relationships applied to RGI are based purely on this area-rule and ignore the classification entirely. This ensures that the model is calibrated over the same type of data that is intended to be applied to. It may be possible to include vertical range into the ice cap rule, as ice caps tend to span a smaller vertical range than glaciers for the same areal extent.

For some glaciers we may have data on several size measures simultaneously, and we will have several options to estimate missing size metrics. E.g. we can estimate V from either L or A, or both. Here I use multiple linear regression (MLR) space to utilize as many predictors as possible in the scaling law used for imputation. Motivated by Bahr et al. (1997) the regressions are done in log-log space. For each glacier only a subset of metrics exists in the inventory and among these the best set of predictors is chosen using a model selection criterion which compares the predictive skill against withheld data. As I am interested in the total volume, I use the Akaike Information Criteria (AIC) calculated for the total volume misfit assuming a 20 % standard uncertainty in the measured volume of the withheld validation dataset. The various size measures are multicollinear by nature, which may potentially affect the performance of regressions, and regularization can be needed. I found however that ridge regression techniques did not improve the skill in this particular study. Validation against withheld data is an efficient guard against multicollinearity and overfitting provided that the validation sample is sufficiently large.

Maritime glaciers are characterized by having a much greater mass turnover than continental glaciers. This will influence the thickness directly, but also indirectly through temperature profiles and water availability. The mass turnover is strongly determined by the vertical mass balance gradient which will be inversely related to temperature variability and thus continentality as this greatly influences how many positive degree

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days will be available for melt at lower elevations. Similar considerations led Oerlemans (2005) to use total annual precipitation as a proxy for vertical mass balance gradient. However, continentality is spatially coherent over much larger distances, and probably shows a closer correspondence unless very local precipitation data is available at each glacier. Further, Braithwaite (1985) provide the physical justification for linking temperature variability to vertical mass balance gradient if a constant temperature lapse rate is assumed. I therefore include continentality (C) as a potential predictor in the imputation models.

To summarize I attempt to optimally predict total volume from a set of potential predictors: A, R, L, and C. I exclude W because it severely restricted the potential number of records in the validation sample where all measures must be present in order to make a fair comparison of models. The meaning of length is ambiguous for ice caps and is therefore excluded for the ice cap scaling laws. Calibrating the models result in the empirical scaling laws listed in Table 2 when using the robust estimator.

4 Results and discussion

From the set of scaling laws I calculate the volume of every glacier in the inventory and calculate the total (Table 3). Volumes are reported in units of meters Sea Level Equivalent (SLE) assuming an ice density of 900 kg m^{-3} and an ocean area of 362×10^6 km^2. I find that the total volume of all glaciers and ice caps range from 0.30 to 0.39 m SLE, depending on the choice of calibration method and inventory choice. This is substantially smaller than the 0.60 ± 0.07 m SLE from Radić and Hock (2010). Different inventories cannot explain this large difference and the issue must be with the different scaling laws applied. In Fig. 1 we see that the Radić and Hock (2010) ice cap volume area scaling law has a positive bias relative to observations, and that the glacier scaling law has a steeper slope which can result in large volumes beyond the calibration range. The units of the constant k are length$^{(3-2k)}$. It is therefore problematic to mix the scaling constant determined from one study, and directly apply it to a scaling law using

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another exponent. Nevertheless this is frequently done (e.g. Radić and Hock, 2010; Slangen and van de Wal, 2011). The constant k can also be interpreted more intuitively as the typical thickness of a glacier with unit area. Extrapolating the scaling laws in Fig. 2 we see that any small change in the slope of the scaling law will have a large impact on the volume (and thus average thickness) of a 1 m^2 sized glacier/ice cap (which would be well beyond the minimum of the plotted range, and far smaller than any real glacier). The uncertainty in the volume-area scaling is huge for a 1 m^2 ice cap, where the regression is virtually unconstrained, and thus mixing constants and exponents from different studies can introduce a large bias. Using km^2-units or expressing the area with respect to a typical reference area greatly reduces the potential error arising from mixing constants and exponents from different studies. We also generally find (regardless of misfit function) that theoretical exponents are greater than observations from nature imply (Table 2, Fig. 2). My interpretation is that the appropriate yield stress is lower for large ice masses than it is for small. A too large exponent leads to a positive bias in the total volume if it is applied to glaciers that are much greater than those in the calibration dataset. This is very important for the estimating total glacier volume as the volume is concentrated in the largest ice masses.

For real glaciers there may be situations where it is not obvious how to divide an ice mass into a distinct number of inventory records. Several valley glaciers may share the same ice field, two valley glaciers may meet in a single tongue, and an ice cap will have many outlet glaciers. The practical problem of how the area is divided among separate inventory records has an impact on the total volume due to the non-linearity of the scaling law. The division issue can be particularly important for volume estimates based on the new Randolph Glacier Inventory (RGI) where each record may not have been carefully divided into distinct units because of the vast number of new glacier outlines the RGI contains. E.g. Devon ice cap has been estimated to hold ~4100 km^3 of ice (Dowdeswell et al., 2004). In RGI, Devon ice cap is represented by 192 separate records, and applying the scaling laws (Table 2) on these records result in a volume of 3200 km^3, whereas treating all these records as a single ice cap results in a volume

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of 5500 km^3. There may be differences in protocol between the regional inventory and the volume-area database which would lead to a systematic bias. This systematic bias is difficult to quantify and hampers the formal calculation of uncertainty, but could plausibly lead to errors in the order 20 % in the total volume for a region. I adopt this 20 % uncertainty estimate which also brackets the RGI sensitivity experiments in Table 3.

Regional estimates of volume is shown in Table 4. There are considerable discrepancies between the RGI and WGI/GLIMS based on volume estimates for Arctic Canada (south), Southern Andes, South Asia (east), and Svalbard. These differences can largely be explained by serious deficiencies in the WGI/GLIMS inventory (see Table 2). E.g. the two largest ice caps in Svalbard containing ~ 8 mm SLE (Dowdeswell et al., 1986; Zhuravlev, 1985) are not represented in the WGI/GLIMS database. The regional volume estimates can be validated against estimates where the major fraction of the volume has been estimated using survey methods. The only such estimate I have been able to find is Björnsson and Pálsson (2008) who estimated the total volume of ice in Iceland to be 9 mm SLE, which compares well with the 8 mm SLE estimated here. It should be noted however that the 4 largest Icelandic ice caps are included in the calibration dataset.

I find that including continentality and vertical range does not improve the fit of area volume scaling sufficiently to justify the extra parameters required in such models by the model selection metric chosen in this study. This may change with a larger dataset of observed volumes to calibrate against, and improved estimates of range and continentality. Including continentality and range are found to improve the skill of length-volume scaling of glaciers. Traditional area-volume scaling is, however, more skillful than length-volume scaling. It may be possible to estimate C from direct observations, and only use reanalysis as a fallback for regions with poor observations. Proper alignment of RGI/GLIMS geometry with the elevation model, and higher quality topography maps should also improve range estimates.

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5 Conclusions

I calibrate scaling laws for the specific purpose of estimating the total volume of all glaciers on Earth. This is applied individually to each record in the Randolph Glacier Inventory which is the first globally complete inventory of glaciers and ice caps. I estimate that the total volume of all glaciers in the world is 0.35 ± 0.07 m SLE. This is substantially less than the 0.60 ± 0.07 m SLE from Radić and Hock (2010), but is in the range of earlier estimates by Raper and Braithwaite (2005). A large part of the difference can be explained by the necessary upscaling of incomplete inventory data which was available to Radić and Hock (2010), but I also identify a source of positive bias in the scaling law used by Radić and Hock (2010) when applied to large ice masses (Fig. 2).

Scaling laws remain the only feasible way of estimating the volume of the vast majority of glaciers. There are probably hundreds of glaciers and ice caps that has been measured, but which has yet to be included in the volume database used in this study (Cogley, personal communication, 2012). The total volume stored in glaciers and ice caps is dominated by relatively few very large and thick ice masses (Fig. 3). Roughly 85 % of the total ice volume is stored in ~1000 RGI glaciers greater than 100 km^2. This is a much more manageable number considering that large ice caps frequently are divided into several RGI records. E.g. Devon ice cap is represented by 192 RGI records and 19 of these are greater than 100 km^2. It may therefore be feasible to get the volume of the majority of these large ice masses on an individual basis through direct measurements (new or published), or by more sophisticated approaches which considers ice flow (e.g. Clarke et al., 2009; Farinotti et al., 2009). This would reduce the uncertainty on the global estimate substantially.

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Table 1. Total glacierized area (km^2) in each region for three inventories. For Radić and Hock (2010) the closest corresponding regions is shown. RGI contains the best available estimate as the only complete inventory. Numbers in parenthesis mark numbers with known inventory issues, or implied from large disagreement with RGI.

	Region	RGI	WGI/GLIMS	Radić and Hock (2010)
1	Alaska	105 224	(50 790)	(79 260)
2	Western Canada and US	15 075	13 691	(21 480)
3	Arctic Canada (north)	114 382	(77 652)	(146 690)
4	Arctic Canada (south)	43 992	42 584	
5	Greenland	97 146	(127 766)	(54 400)
6	Iceland	11 133	11 053	11 005
7	Svalbard	35 392	(12 807)	36 506
8	Scandinavia	2888	2363	3057
9	Russian Arctic	53 720	(41 815)	56 781
10	North Asia	2898	(3457)	2902
11	Central Europe	2148	2706	3045
12	Caucasus and Middle East	1344	1433	1397
13	Central Asia	66 245	(96 916)	
14	South Asia (west)	38 518	34 079	114 330
15	South Asia (east)	22 766	(31 638)	
16	Low Latitudes	4184	(3029)	(7060)
17	Southern Andes	33 951	(9542)	(29 640)
18	New Zealand	1284	1110	1156
19	Antarctic and Subantarctic	134 596	(95 369)	(172 740)
	Total	786 882	(659 794)	741 448

Table 2. Volume scaling laws resulting from calibrations minimizing the absolute volume deviation. These relationships are expressed in km, km^2 and km^3 units. More decimal places are retained than is significant to facilitate conversion to other units. RGI does not distinguish between glaciers and ice sheets but only whether their area $> 25\,km^2$.

	RGI	WGI/GLIMS
Ice caps/$A > 25\,km^2$	$V = 0.059 \cdot A^{1.19}$	$V = 0.053 \cdot A^{1.2}$
		$V = 168 \cdot R^{3.9}$
Glaciers/$A \leq 25\,km^2$	$V = 0.045 \cdot A^{1.13}$	$V = 0.059 \cdot A^{1.22}$
		$V = 0.57 \cdot L^{0.167} \cdot C^{-0.86}$
		$V = 2.7 \times 10^{-7} \cdot R^{4.7} \cdot C^{5.2}$ *

* Marks a scaling law with symptoms of overfitting. This relationship is only applied to a neglible number of glaciers where both A and L are missing.

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Table 3. Calculated total volume of two glacier inventories and three methods of calibrating the scaling law. The robust least absolute deviation estimate based on RGI is considered to be the best as there are serious inventory deficiencies with WGI/GLIMS (see text and Table 1).

Inversion misfit function	RGI (m SLE)	WGI/GLIMS (m SLE)
Least squares, log(V)	0.34	0.27
Least squares, V	0.41	0.37
Least absolute deviation, V	0.35	0.31

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Table 4. Estimated total volume of ice (mm SLE) by region (see Fig. 1) for the two inventories. Numbers in parenthesis mark numbers with known inventory deficiencies (see text). The volumes for the closest corresponding regions estimated by Radić and Hock (2010) are shown for comparison. RGI estimates are considered to be best but may have uncertainties in the order of 20 % (see text).

	Region	RGI	WGI/GLIMS	Radić and Hock (2010)
1	Alaska	43.5	(28.5)	(68)
2	Western Canada and US	2.6	2.9	(4.7)
3	Arctic Canada (north)	60.8	(45.3)	(199)
4	Arctic Canada (south)	14.3	27.4	
5	Greenland	49.1	(63)	(44)
6	Iceland	7.8	10.5	12
7	Svalbard	13.4	(4.6)	26
8	Scandinavia	0.8	0.5	0.56
9	Russian Arctic	35.7	(25)	43
10	North Asia	0.5	(0.6)	0.42
11	Central Europe	0.3	0.5	0.48
12	Caucasus and Middle East	0.2	0.3	0.22
13	Central Asia	20.5	(22.8)	
14	South Asia (west)	9.8	10.1	31
15	South Asia (east)	4.1	(7.5)	
16	Low Latitudes	0.5	(0.5)	(0.86)
17	Southern Andes	10.3	(2.4)	(20)
18	New Zealand	0.3	0.2	0.21
19	Antarctic and Subantarctic	74.2	(53.9)	(178.9)

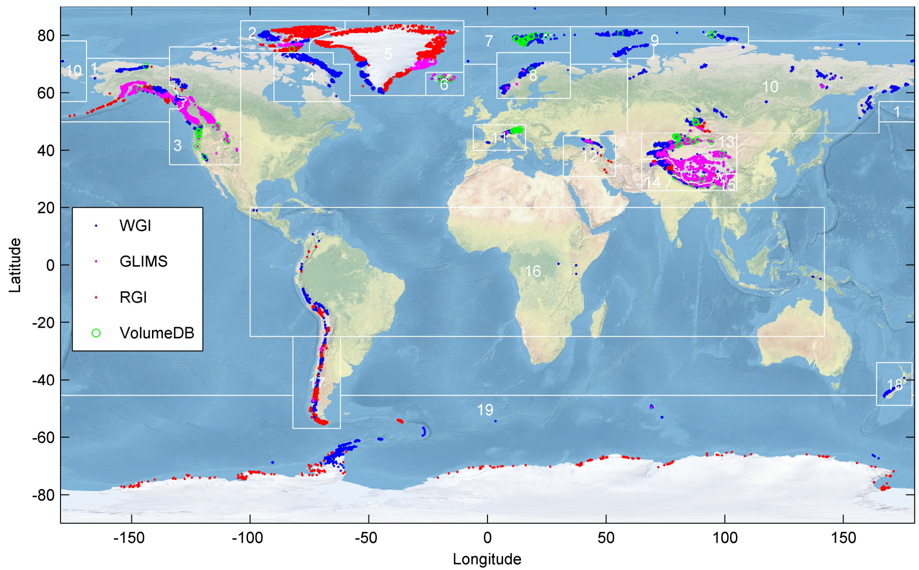

Fig. 1. Spatial distribution of glaciers in the four glacier inventories used in this study. GLIMS glaciers that are already in WGI are not plotted and neither is RGI glaciers overlapping with WGI and GLIMS. VolumeDB refers to the updated Cogley (2012) area volume database used for calibration is shown as green circles (some positions are approximate). White boxes show the regions as defined by Arendt et al. (2012) and region numbers are listed in Tables 1 and 4.

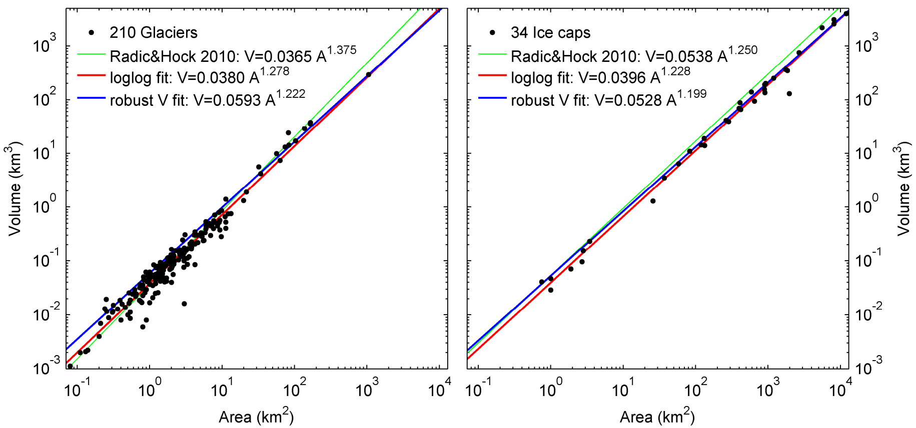

Fig. 2. Area volume scaling for glaciers (left) and ice caps (right) calibrated to a collection from Cogley (2012). The y-axis is the same so that the smaller volumes for a given area of ice caps can be seen. The fitted lines are from least squares regression of log(V) and least absolute difference in volume. For comparison the scaling law used in Radić and Hock (2010) is also shown. Theoretical scaling law exponents (Bahr et al., 1997) are generally higher than what is observed in nature.

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An estimate of global glacier volume

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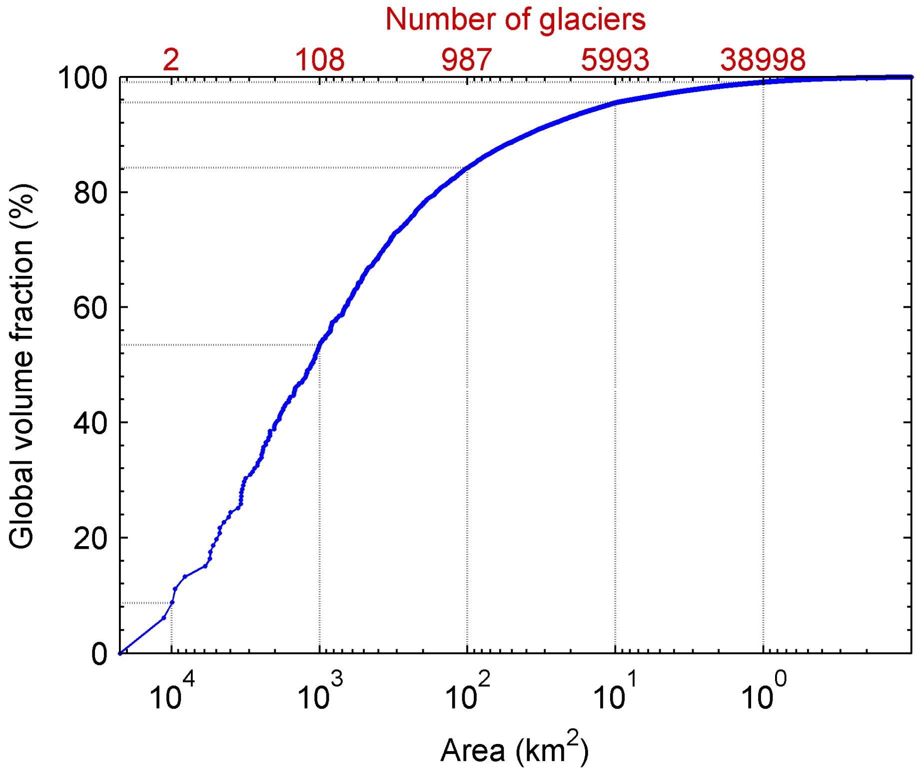

Fig. 3. The volume fraction stored in all the glaciers larger than a given area. Red numbers show how many RGI records this corresponds to.

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