Completing the World Glacier Inventory

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ABSTRACT. An inventory of the surface area and volume of the world's glaciers, outside Greenland and Antarctica, was part of the International Hydrological Decade (1965-74). It was considered essential to an understanding of the role played by glaciers in the hydrological cycle and was to be repeated every 50 years to detect change. To date, 46% of the estimated total glacier area has been inventoried and made available through the World Glacier Monitoring Service and the US National Snow and Ice Data Center. As the original inventory method was too time-consuming and inapplicable for some areas, a simplified method was developed in the early 1980s using satellite images. The Global Land Ice Measurements from Space (GLIMS) project now covers 34% of the estimated glacierized area outside Greenland and Antarctica. Both inventory efforts have made good progress and contributed substantially to our knowledge of glaciology and its related sciences, but global coverage is still incomplete. If both inventories are combined, 46% of the world's glacierized area is still missing; 26% is covered by both methods, which allows the quality of the satellite-based and semi-automatic inventories to be assessed by comparison. About 95 000 glaciers remain to be inventoried, of which about half are in the Canadian Cordillera, South America and the Canadian Arctic Islands. As the cryosphere is changing rapidly, it is of the utmost importance to complete the global glacier inventory as soon as possible, and identify an appropriate repeat cycle.

INTRODUCTION

The World Glacier Inventory (WGI), one of the activities planned for the International Hydrological Decade (1965-74), was established to obtain an accurate assessment of the amount, distribution and variation of all snow and ice masses. One of its main objectives was to better understand the role of snow and ice in the global water balance. To achieve this, the International Commission on Snow and Ice (ICSI) was asked to prepare guidelines for the compilation of a world inventory of perennial ice and snow masses. A Working Group, chaired by F. Müller, was established by ICSI to formulate standardized procedures (UNESCO/IAHS, 1970). To facilitate international participation in the WGI, a Temporary Technical Secretariat (TTS) for the World Glacier Inventory was established by UNESCO, the United Nations Environment Programme (UNEP) and the International Commission on Snow and Ice (ICSI) at the Federal Institute of Technology (ETH) in Zürich in 1973. The TTS was responsible for compiling, and archiving, data contributed by the participating national glacier-inventory groups. At the same time, the TTS organized training courses for personnel engaged in inventory work worldwide. Although WGI activities initially focused on smaller mountain glaciers and ice caps, the guidelines were written with a view to their future application to parts of Greenland and Antarctica. Further, it was planned to repeat similar inventories every half-century to record changes. To accelerate the inventory work, remote-sensing techniques and automated computer processing were adopted in the 1980s, laying the foundation for the Global Land Ice Measurements from Space (GLIMS) and GlobGlacier projects. The glaciological data obtained through the WGI are available from the World Glacier Monitoring Service (WGMS) in Zürich, Switzerland, and the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, USA.

PRESENT STATUS OF WGI

In the 40 years since the WGI was launched, and the 25 years since simplified inventory methods were introduced, both efforts have made good progress and contributed substantially to our knowledge of glaciology and its related sciences. Although inventory data are stored in identical formats at both the WGMS and NSIDC, access to these data differs. For the former, users must contact the WGMS to have the data forwarded electronically; data at NSIDC can be accessed directly through its website. The quantity of available data varies with time as new data are added. As of 1 September 2008, the WGI held information on about 107 000 glaciers in 28 countries; of these, 11 countries had complete inventories. Of the estimated $554.2~\times 10^3\,km^2$ total surface area of glaciers, the WGI covers 46%, GLIMS 34%, and 26% is covered by both projects; 54% of the glacierized area is covered by combining WGI and GLIMS data.

Although one of the data fields in the original inventory manual (Müller and others, 1977) was mean depth, there is no column for volume or mean depth in the WGMS and NSIDC files. Some national inventories (e.g. Switzerland and China) have used their own methods for estimating volume. At some stage, possibly because of concerns over its accuracy, or lack of homogeneity in the different estimation techniques, volume was dropped from the world inventory dataset. However, for a number of critical questions (e.g. sea-level change), glacier volume is essential, so renewed efforts must be made to consider how glacier volume can be estimated with confidence.

VOLUME ESTIMATION WITH WGI DATA

The WGI data are organized with respect to each country. However, the characteristics of the glaciers differ greatly within a country, especially when the country is large and

Table	1.	Overview	of glacie	r area	and	volume	and	WGI	completion	rate.	Bold	numbers	are	quantities	from	the	completed	national
invent	tori	es. Italic n	umbers ar	e com	pletic	on rates	deci	mal)										

	Number of glaciers	Area in WGMS (1989)	Area in WGI	Completion rate	Volume in WGI	Mean depth	Est. total volume	Best area est.
		km ²	km ²		4 km ³	m	4 km ³	km ²
South America								
Tierra del Fuego	244	21 200	1221.7	0.058	201.031	165	3488.465?	21200
Argentina north of 47.5°S	2350	1385	863.11	0.623	43.396	50	69.636?	1385
Chile north of 46° S	1050	743	756.8	1.000	39.603	52	39.603	756.8
Bolivia	1697	566	509.5	1.000	17.020	33	17.020	509.5
Peru	1679	1780	1131.1	0.635	41.621	37	65.499?	1780
Ecuador	114	120	110.8	1.000	3.538	32	3.538	110.8
Colombia	106	111	18.61	0.168	0.478	26	2.851?	111
Venezuela	7	3	2.51	1.000	0.079	31	0.079	2.51
Middle and North America								
Mexico		11		0.000		183	2.013?	11
USA (with Alaska)	2592	75 283	12 568	0.168	3360.922	266	19988.963?	75 283
Canada	15054	200806	36405	0.181	5739.357	158	31 657.666?	200 806
Africa	60	10	10.85	1.000	0.221	20	0.221	10.85
Europe								
Iceland		11260	11 200	1.000		326	3650.000	11200
Svalbard	895	36612	33 666	1.000	7656.075	227	7656.075	33 666
Scandinavia (with Jan Mayen)	2410	3174	3058	1.000	167.336	55	167.336	3058
Alps	5426	2909	3059.71	1.000	146.076	48	146.076	3059.71
Pyrenees	108	12	11.43	1.000	0.182	16	0.182	11.43
Ex-USSR and Asia								
Ex-USSR	20 908	77 223	82128	1.000	23934.998	291	23 934.998	82 128
Afghanistan, Iran, Turkey	610	4000	472	0.118	16.569	35	140.415?	4000
Pakistan, India	303	40 000	1898.4	0.047	146.490	77	3086.599?	40 000
Nepal, Bhutan	226	7500	2983	0.398	301.145	101	757.153?	7500
China	46 377	56 481	60 035	1.000	5600.000	94	5600.000	59425
Indonesia		7		0.000			?	7
Oceania								
New Zealand	3149	860	1157.9	1.000	61.893	53	61.893	1157.9
Sub-Antarctic islands		7000		0.000		183	1281.000?	7000
Total	105 365	549056	253 357.42	0.457	47 478.03	184	101 817.28	554179.5

the climatic conditions have large regional differences. Table 1 provides an overview of glacierization with respect to glacier area and volume; this is illustrated graphically in Figure 1. These summaries indicate where efforts are needed to complete the global inventory. Although volume can be estimated using the WGI glacier features (e.g. location, altitude and surface area), its accuracy is questionable.

If the ultimate objective is to obtain a global ice volume, the WGI contains about the best data available. The advantage is its generally homogeneous nature and availability for computer processing. However, options for estimating volume are limited. With respect to those processes that determine the shape of the glacier, and hence its thickness and volume, some key information (e.g. mass balance, ice temperature and bottom topography) is not included in the inventory. It is also unrealistic to expect that the number of glaciers for which accurate ground surveys will be carried out will increase greatly in the near future. As a first step, we try to estimate the ice volume based solely on the information available in the WGI. The simplest approach is to exploit the relationship between mean depth and the surface area of each glacier, the latter being available for all glaciers. The mean depth, H, is defined as the ratio of the volume, V, to the surface area, S. In the present report, two different equations with different bases are used. Chen and Ohmura (1990) derived a relationship between H and S using a statistical method based on data from 67 glaciers, which at that time had been well measured either by ground-penetrating radar (GPR) or seismic soundings. Bahr and others (1997) proposed a similar equation using dynamic considerations. This work was calibrated empirically with data from more recently sounded glaciers. The mathematical forms of these equations are shown in Figure 2; a similar relationship used at the WGMS is added for comparison. Figure 2a represents the range of glaciers smaller than 100 km², while Figure 2b represents the relationship for larger glaciers up to 1000 km². The circles show results of more recent highresolution GPR soundings, but data from these glaciers were not used for deriving the present equations. The general trend is that for most small to medium glaciers the Bahr equation has a closer affinity to the recent soundings,



Fig. 1. Global distribution of glacier ice outside Greenland and Antarctica. The columns represent the total regional ice volume. The area of the column base represents the total surface area and the column height represents the mean glacier thickness. The numbers indicate the number of glaciers in each region.



Fig. 2. Relationships between glacier surface area and ice volume, for glaciers $\leq 100 \text{ km}^2$ (a) and $>100 \text{ km}^2$ (b). Curves represent the relationships as proposed by Chen and Ohmura (1990) (dark, dotted), D. Bahr (personal communication, 2008) (light, no dots) and WGMS (1989) (light, dotted). Circles represent recent radio-echo sounding results compiled by A. Fischer (large circles) and A. Ohmura (small circles).

while for larger glaciers the Chen/Ohmura equation has a better fit. Table 2 presents an estimate of volume for each region and the world. The total volume values for the regions are multiplied by the ratio of the total glacier area of the region to the sum of the surface areas of the inventoried glaciers, in an effort to simulate the volume for an entire region. This estimation can be justified only when the inventoried region represents the entire region concerned. The difference between the two equations is about 30%. To close the difference, one might use another influential variable (e.g. the mean surface gradient). To improve these equations it will be necessary to prioritize the glaciers by size, i.e. by those that are most influential on the total ice volume. For example, the Chinese Glacier Inventory shows that priority should be given to glaciers 1-30 km² in area. Glaciers falling within this relatively narrow band contribute about 50% of the total ice volume, although only 25% of the glaciers belong in this range. This result also shows how important it is to establish the mean depth/surface-area ratio for glaciers with areas around 30 km². At present the global glacier ice volume outside Greenland and Antarctica is estimated at $100-130 \times 10^3$ km³, corresponding to 25-32 cm sea-level equivalent.

OTHER APPLICATIONS

The large number of glaciers registered in the WGI makes it possible to investigate statistical features of glaciers by region or hydrological basin. This is especially useful for estimating discharge from a glacierized basin and can be computed for individual glaciers. It is also possible to construct a generic glacier representative of a relatively large region (e.g. a drainage basin or a mountain range). Müller and others (1976) constructed such a hypothetical glacier using an altitude vs area relationship. Shi and others (2008) also took a drainage basin, but expressed the glacier characteristics by number frequency, surface area and volume as a function of surface-area classes that are defined as an integer to the power of 2. The occurrence frequency distribution Shi and others scaled is extremely interesting, as multiplication of the frequency by $S^{-\alpha}$ immediately gives a representation of the area and volume distribution, where α is a constant. $\alpha = 1$ provides the area distribution, and α = 1.375 the volume distribution, after Bahr's equation.

CONCLUSION AND RECOMMENDATION

The most important task of the WGI is to complete the project at the global scale as soon as possible. The estimated number of glaciers still to be measured for each region is presented in Table 3. Progress on the inventory for the following regions is urgently needed: the Canadian Cordillera (~54000 glaciers to be inventoried), followed by South America (11600), the Canadian Arctic (9600), India and Pakistan (6100) and Alaska (5300). These regions should be given an especially high priority. The total number of uncatalogued glaciers in these five regions accounts for 90% of the glaciers still to be inventoried. After completion of inventories in these regions, the WGI would have information on >95% of the world's glaciers. The inventory should be extended to Greenland and Antarctica. In fact such an inventory has already been done for Greenland and it only remains to incorporate these data into the existing WGI.

Table 2. Comparison of volume estimations by two equations. Numbers in bold are volumes for regions with a completed inventory, the other numbers are for regions with partial inventories, while the line for Iceland has values computed by the Icelandic inventory team

	Est. total volume by Chen/Ohmura km ³	by D. Bahr km ³
South America Tierra del Fuego Argentina north of 47.5° S Chile north of 46° S Bolivia Peru Ecuador Colombia Venezuela	3488.5 69.6 39.6 17.0 65.5 3.5 2.9 0.1	4581.5 86.3 49.1 20.6 79.5 4.2 3.4 0.1
<i>Middle and North America</i> Mexico USA (with Alaska) Canada	2.0 19989.0 31657.7	2.0 26 870.8 41 581.3
Africa Europe Iceland Svalbard Scandinavia (with Jan Mayen) Alps	0.2 3650.0 7656.1 167.3	0.3 3650.0 10 207.9 207.6
Pyrenees Ex-USSR and Asia Ex-USSR Afghanistan, Iran, Turkey Pakistan, India Nepal, Bhutan China Indonesia	0.2 23 935.0 140.4 3086.6 757.2 4034.2	32 786.0 169.9 3888.5 966.4 5087.0
<i>Oceania</i> New Zealand Sub-Antarctic islands Total	61.9 1281.0 100251.4	77.2 1281.0 131 781.3

There is also a partial inventory for some parts of Antarctica; future work here should concentrate initially on valley glaciers and the small ice caps. Consideration will need to be given to how the major ice streams and ice shelves can best be delineated and measured. Satellite remote sensing will be the key to completion of a comprehensive inventory and there may be some other components that can be adopted in future inventories. During the last half-century there has been a tremendous advance in glaciological knowledge and the supporting technology. Previously abandoned key components (e.g. the equilibrium-line altitude (ELA) and ice volume) may now be readopted with much higher confidence. In view of the rapid changes taking place in the cryosphere, the 50 years originally conceived as an appropriate re-inventory interval needs to be reconsidered. The rapid adoption of satellite-based techniques should allow for the much more frequent inventories that are now desired.

Table 3. Estimation of the glaciers remaining to be inventoried. Bold indicates completed inven
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Region	Surface area	Est. volume	Mean depth	WGI completion rate	Total number of glaciers	Glaciers to be treated
	10^3km^2	10^3km^3	m	%		
Greenland (Total) (Ice sheets) (Mountain glaciers and ice caps)	1748 1699 49	2931	1677			
Iceland	11.20	3.65	326	100		
Scandinavia Alps Pyrenees and Cordillera Cantabrica	3.10 3.10 0.01	0.167 0.146 10 ⁻⁴	53.9 47.1	100 100 100	2410 5426 108	
Jan Mayen Svalbard	33.67	10 ⁻² 7.66	227.3	0 100	894	? Not many
Zemlya Frantsa Yosifa Novaya Zemlya Severnaya Zemlya and Ostrov Ushakova Ostrava de Longa, Novosibirskiye Ostrova Ostrov Vrangelya	13.76 23.65 19.37 0.08 0.00	1.907 11.133 6.603 0.007 0.000033	138.6 470.8 341.0 86.4 8.3	100 100 100 100 100	1008 685 294 15 101	
Caucasus Severniy Ural Ex-USSR in Asia	1.39 0.02 23.86	0.066 0.00037 4.217	47.5 176.8	100 100 100	1533 84 17 190	
Canadian Arctic Islands North American Cordillera Alaska Mexico	151.76 49.61 74.72 0.01	27.56906 4.5825 20.45017	181.8 92.3 273.6	17 21 16	11 588 69 652 6556	9600 55 000 5400
Afghanistan, Iran, Turkey India, Pakistan Bhutan, Nepal China Indonesia	4 40 7.50 59.43 0.01	0.14569 3.07622 0.74046 5.600	36.0 76.9 100.9 94.2	12 5 41 100	5169 6384 568 46 377	4500 6100 300
Africa	0.01	10 ⁻⁴	21	100	59	
New Zealand	1.16	0.062	54	100	3149	
South America	25.86	3.687	143	18	14 145	11 600
Sub-Antarctic islands	7.00	1.2	171	0		500-1500
Antarctica	12 300	24700	2010			
Total excluding Greenland and Antarctica	554.18	102.670	181		193 396	~95 000

REFERENCES

- 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.
- Chen, J. and A. Ohmura. 1990. Estimation of Alpine glacier water resources and their change since the 1870s. *IAHS Publ.* 193 (Symposium at Lausanne 1990 – *Hydrology in Mountainous Regions*), 127–135.
- Müller, F., T. Caflisch and G. Müller. 1976. *Firn und Eis der Schweizer Alpen: Gletscherinventar.* Zürich, Eidgenössische Technische Hochschule. (Geographisches Institut Publ. 57.)
- Müller, F., T. Caflisch and G. Müller. 1977. Instructions for the compilation and assemblage of data for a world glacier

inventory. Zürich, ETH Zürich. Temporary Technical Secretariat for the World Glacier Inventory.

- Shi, Y., S. Liu, B. Ye, C. Liu and Z. Wang, eds. 2008. Concise glacier inventory of China. Shanghai, Shanghai Popular Science Press.
- UNESCO/International Association of Scientific Hydrology (IASH). 1970. Perennial ice and snow masses: a guide for compilation and assemblage of data for a world inventory. Paris, UNESCO/ International Association of Scientific Hydrology. (Technical Papers in Hydrology 1.)
- World Glacier Monitoring Service (WGMS). 1989. World glacier inventory: status 1988, ed. Haeberli, W., H. Bösch, K. Scherler, G. Østrem and C.C. Wallén. IAHS(ICSI)–UNEP–UNESCO, World Glacier Monitoring Service, Zürich.