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VARIABLES



GLACIERS

Glaciers and Ice Caps



“The Hintereisferner in Austria is among the best investigated glaciers in the monitoring network with length change and mass-balance measurements reaching back to the mid-19th and mid 20th century, respectively. Photo taken on 12 September 2006 by A. Lambrecht.”

GLACIERS

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List of Acronyms

AAR	Ratio of accumulation area to total glacier area
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ECVs	Essential Climate Variables
ELA	Equilibrium Line Altitude
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
FAGS	Federation of Astronomical and Geophysical Data Analysis Services
GCM	Global Climate Model
GCOS	Global Climate Observing System
GHOST	Global Hierarchical Observing Strategy
GTOS	Global Terrestrial Observing System
GIS	Geographic Information System
GLIMS	Global Land Ice Measurements from Space
GPS	Global Positioning System
GTN-G	Global Terrestrial Network for Glaciers
IACS	International Association of Cryospheric Sciences
ICSU	International Council for Science
IGOS	Integrated Global Observing Strategy
IPCC	Intergovernmental Panel on Climate Change
IUGG	International Union of Geodesy and Geophysics
Landsat TM/ETM+	Landsat Thematic Mapper/Enhanced Thematic Mapper+
LIA	Little Ice Age
NSIDC	National Snow and Ice Data Center
RCM	Regional Climate Model
UNESCO	United Nations Educational, Scientific and Cultural Organization
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service

Executive Summary

Changes in glaciers provide some of the clearest evidence of climate change, constitute key variables for early-detection strategies in global climate-related observations, and have the potential to cause serious impacts on sea level, the terrestrial water cycle and societies dependent on glacier melt water (GCOS 2004). Perennial surface ice on land includes glaciers and ice caps as well as the two continental ice sheets with their ice shelves, with fundamental differences in time-scales and processes involved. Due to their large areas and volumes, the two continental ice sheets in Greenland and Antarctica actively influence the global climate and react to climatic changes over time-scales of millennia. On the other hand, glaciers and ice caps with their smaller volumes and areas typically react much faster (few decades) to climatic changes.

Internationally coordinated monitoring of glaciers and ice caps (i.e. their outlet glaciers) was initiated in the late nineteenth century. The active compilation and publication of standardized data has resulted in unprecedented datasets on their distribution and changes. The international data collection through a scientific collaboration network is coordinated within the Global Terrestrial Network for Glaciers (GTN-G), a component of the Global Climate/ Terrestrial Observing Systems (GCOS/GTOS). The GTN-G is run by the World Glacier Monitoring Service (WGMS) at the University of Zurich, Switzerland, in collaboration with the US National Snow and Ice Data Center (NSIDC) at the University of Colorado, Boulder, USA, and the Global Land Ice Measurements from Space (GLIMS) initiative, hosted at NSIDC. The core datasets comprise standardized information on the spatial distribution of the ice cover (extent in square kilometres) at a certain point in time (glacier inventories), changes in terminus position (horizontal length change in metres) and mass balance (thickness

change in metres of water equivalent). Several additional glacier attributes and meta-information is provided in the data sets. Glacier inventories are used to estimate the overall ice area and volume and, when available for more than one point in time, to assess (decadal to centennial) glacier changes for entire mountain ranges. Length change and mass balance measurements are carried out at a relatively small set of glaciers but with high temporal (annual) resolution. Thereby, glacier front variations constitute an indirect, delayed and filtered but also enhanced and easily observed signal of climate change, whereas glacier mass balance is a more direct and undelayed signal of annual atmospheric conditions.

At present, detailed inventories are available for around the 1960s to 1970s for approximately 100 000 glaciers and ice caps throughout the world, with an overall area of some 240 000 km² as well as preliminary estimates of the other glacierized regions, mainly based on aerial photography, early satellite imagery, and maps. In addition, digital outlines of 83 000 glaciers covering about 261 000 km² have been compiled (status of June 2008), mainly from more recent satellite data, in the GLIMS database. The total number and area of glaciers and ice caps are estimated at about 160 000 and some 685 000 km², respectively. Glacier fluctuations are documented by a standardized dataset of approximately 36 000 length change observations from about 1 800 glaciers, reaching back to the nineteenth century, and from approximately 3 400 mass balance measurements from 230 glaciers covering the past six decades (WGMS, 2008a). The status of the datasets is periodically published and all data are available in digital form and at no charge upon request. The main shortcomings of the presently available datasets are: (i) the incompleteness of a detailed global inventory of glaciers and ice caps; (ii) the lack of repeated detailed inventories which are needed to assess the glacier changes over entire mountain ranges, and

(iii) the strong bias of available glacier length change and mass balance measurement series towards the Northern Hemisphere and Europe.

Change assessments based on integrative analysis of the available *in situ* measurement with remotely sensed data conclude that glaciers around the globe show a centennial trend of glacier retreat from the Little Ice Age moraines, which mark maximum Holocene glacier extents in many mountain ranges, and an accelerated ice wastage since the mid-1980s. On a decadal time-scale, glaciers in various regions have shown intermittent re-advances (e.g. around the 1920s and 1970s). However, under current climate change scenarios, the ongoing trend of worldwide and fast glacier shrinkage is most likely of non-periodic nature, and may lead to the deglaciation of large parts in many mountain ranges in the coming decades.

Over the past decades of glacier monitoring, several manuals and guidelines have been published describing the terminology and methodology to carry out glacier inventories, mass balance and front variation measurements. These reference documents are listed and made available through WGMS, NSIDC and GLIMS.

Recommendations

In view of the expected rapid changes, the incompleteness of the global inventory of glaciers and ice caps, and the bias of the available fluctuation measurements, it is crucial to:

- Make *in situ* and remotely sensed glacier measurements with related meta-data readily available according to the existing international standards and guidelines.
- Complete a global detailed glacier inventory and compile repeat inventories for the assessment of glacier changes.
- Continue long-term length change and mass balance measurements.
- Extend the present *in situ* network with additional and re-initiated long-term series.
- Improve the metadata and quantify the uncertainties of the datasets.
- Make systematic use of remote sensing and geoinformatics to assess the representativeness of *in situ* observation series for their mountain ranges.
- Encourage numerical modelling studies to use the available datasets for linking the local process studies with global coverage, glacier fluctuations with climate forcing and to bridge the gap between global/regional climate models and local glacier models for impact studies.
- Strengthen the cooperation of the organizations involved in the international glacier monitoring within GTN-G.
- Secure long-term national and international funding for long-term observation series and for the services running the GTN-G.

Note expanded recommendations in section 8.

The dramatic climate changes estimated for the twenty-first century in the latest IPCC report may cause major changes in glaciers with considerable impacts on landscape evolution, fresh water supply, natural hazards, and sea level. In order to face the related challenges for glacier monitoring in the twenty-first century, it is required that systematic use is made of the rapidly developing new technologies in remote sensing and geoinformatics and that these techniques are related to the traditional field observations.

1. Introduction

Glaciers are an inherent component of the culture, landscape, and environment in high-mountain and polar regions. They represent a unique resource of fresh water for agricultural, industrial and domestic use, an important economic component of tourism and hydro-power production, but can also constitute a serious natural hazard. As the ice of most glaciers (by number) is close to melting point, they react very sensitively to climate fluctuations, and thereby provide some of the clearest evidence of ongoing climate change. For these and other reasons they have been selected among the essential climate variables (ECVs) in the terrestrial domain within the Global Climate Observing System (GCOS 2004).

2. Definition and units of measure

Perennial surface-ice on land is one of the cryospheric components and can be categorized into (a) ice sheets and ice shelves and (b) glaciers and ice caps (cf. IPCC 2007). The reasoning for this separation includes the fundamental differences in time-scales and processes involved with both components. While the two continental ice sheets in Greenland and Antarctica actively influence the global climate, glaciers and ice caps do only react to the climatic forcing, typically on time scales of a few decades and centuries. The focus of this chapter is on the ECV glaciers and ice caps. Note that the term glacier in this context is used as a synonym for different types of glaciers such as outlet, valley, and mountain glaciers, glacierets and perennial snow fields (cf. WGMS 1989, 2008b).

A glacier is defined as a mass of surface ice on land flowing downhill (by internal deformation and often sliding at the base) and constrained by the

surrounding topography (e.g. the sides of a valley or surrounding peaks); the bedrock topography is the major influence on the dynamics and surface slope of a glacier. Generally, a glacier is maintained by accumulation of snow at high altitudes that is balanced by ice loss due to melting at low altitudes, dry calving or discharge into lakes or the sea (IPCC 2007).

An ice cap is a dome-shaped ice mass covering the underlying bedrock. It is considerably smaller in extent than the two continental ice sheets (IPCC 2007). Since the same measurement principles are applicable to glaciers and ice caps, the term “glaciers” represents both features in the following.

To determine glacier changes, the following three primary variables are periodically measured:

- specific mass balance, in water equivalent (m)
- front variation (m)
- area (km).

The specific glacier mass balance (i.e. change in thickness averaged over the entire glacier) is the direct and undelayed signal on the glacier surface to the annual atmospheric conditions, and can be compared between different glaciers. Observations of glacier front variations (i.e. advance or retreat of the glacier tongue) – an indirect, delayed and filtered glacier reaction to more long-term (i.e. climatic) changes – are used to extend the mass balance observations in space and (back) in time (cf. Hoelzle *et al.* 2003, Haeberli and Holzhauser 2003). Cumulative length changes over some years do also clearly document the effects of climate change for the numerous stakeholders and the general public. The overall glacierized area (i.e. the distribution of perennial ice at a certain point in time) is needed to extrapolate the measured glacier changes to entire mountain ranges (e.g. Paul *et al.* 2004) or to the entire world, e.g. for the calculation of hydrological balances or of potential sea level rise.

Other variables measured to understand the glacier distribution, behaviour and related processes include:

- location
- exposition
- lowest and highest glacier point
- length
- winter/summer balance
- altitude of the equilibrium line altitude (ELA)
- ratio of accumulation area to total glacier area (AAR)
- and further parameters (see IGOS 2006, Rau *et al.* 2005, WGMS 1989, WGMS 2007, WGMS 2008b).

3. Existing measurement methods, protocols and standards

3.1 *In situ* measurement

Specific mass balance

Within GTN-G, the combination of the direct glaciological and the geodetic methods has been proven to be a feasible approach providing relevant results. This approach combines the strengths of the direct glaciological method (high temporal resolution, insight into glacier processes) with the ones of the geodetic method (spatial representativity over a longer time period). In regions without available measurements, a series of other methods (e.g. flux method, hydrological method, indirect methods, modelling from climate records) are used to estimate glacier mass balance. A description of the different methods, their parameters, as well as their specific

strengths and weaknesses can, for example, be found in Østrem and Brugman (1991), Dyurgerov (2002), and Kaser *et al.* (2002). Kaser *et al.* (2006) and Zemp *et al.* (2009) give short overviews of the uncertainties of the combined approach, the mass balance estimates for the past six decades and discuss the corresponding up-scaling to global extent (i.e. sea-level equivalents).

Glacier mass balance measurements on entire glaciers started in the second half of the 20th century (1946). The WGMS regularly collects the measured mass balance data and makes it readily available for the scientific community and the wider public. Preliminary mass balance values are published annually on the WGMS website, and the updated mass balance series is published every two years since 1991 in the “Glacier Mass Balance Bulletin” (WGMS 2007 and earlier volumes). Detailed standardized information on annual/winter/summer balance, equilibrium line altitude, accumulation area ratio, and a large amount of meta-information have been collected and published since 1967 in five-year intervals in the ‘Fluctuations of Glaciers’ series (WGMS 2008b and earlier volumes).

Front variation

Regular quantitative observations of glacier front variations (i.e. length changes) started back in the 1880s. The variation of the glacier terminus position is (multi-)annually measured in geodetic ground surveys (tape, theodolite, GPS, etc.) and ideally combined with terrestrial/aerial photogrammetry or remote sensing methods which are repeated on a decadal time scale. Standardized front variation data has been regularly collected and published by the WGMS and its predecessor organizations in the ‘Fluctuations of Glaciers’ series since 1967 (WGMS 2008b and earlier reports) as summarised in Hoelzle *et al.* (2003) and WGMS (2008a).

Protocols and standards

Each fall, the WGMS sends out a call-for-data for information on glacier fluctuations from the preceding observation period. This one-year retention period allows the investigators to properly analyse and publish their data before making it available to the scientific community and the wider public. Guidelines for the data collection and submission, a digital data submission form, and notes on the completion of the data sheets are available from the WGMS Web site. The most relevant guidelines for glacier front variation and mass balance measurements are:

- Forel, F.A. (1895): Instructions pour l'observation des variations des glaciers. Discours préliminaire. Archives des Sciences physiques et naturelles, XXXIV, 209-229.
- Kaser, G., Fountain, A., and Jansson, P. (2003): A manual for monitoring the mass balance of mountain glaciers with particular attention to low latitude characteristics. A contribution from the International Commission on Snow and Ice (ICSI) to the UNESCO HKH-Friend programme. IHP-VI, Technical Documents in Hydrology, No. 59, UNESCO, Paris. 107 p. + Appendices.
- Østrem, G. and Stanley, A. (1969): Glacier mass balance measurements. A manual for field and office work. Canadian Department of Energy, Mines and Resources, Norwegian Water Resources and Electricity Board. 125 pp.
- Østrem, G. and Brugman, M. (1991): Glacier mass-balance measurements: a manual for field and office work, NHRI Science Report.
- UNESCO (1970/73): Combined heat, ice and water balances at selected glacier basins. Part I: A guide for compilation and assemblage of data for glacier mass balance measurements. Part II: Specifications, standards and data exchange. UNESCO/ IAHS Technical Papers in Hydrology 5.
- WGMS (2008): Submission of glacier fluctuation

data to the World Glacier Monitoring Service: general guidelines, attribute descriptions and digital data submission form.

Available from www.wgms.ch/datasub.html

3.2 Remote sensing

Area

The need for a worldwide inventory of existing perennial ice and snow masses was first considered during the International Hydrological Decade declared by UNESCO for the period of 1965-1974. In 1989, a status report on the World Glacier Inventory (WGI) was published by the WGMS (WGMS 1989) including detailed information of about 67 000 glaciers, both mainly based on aerial photography and maps from the 1950s to 1980s, of varying quality. In total, glaciers and ice caps were estimated to a number of about 160 000, covering an area of about 685 000 km² around the 1970s (Dyurgerov and Meier, 2005). Basic information for approximately half of these glaciers (~100 000) is currently stored in the WGI database and is available in digital form via the WGMS Web site (www.wgms.ch/wgi.html), mirrored at the NSIDC. Many regions are still missing, although preliminary overview data (mainly total area) has been compiled for these. For assessment of glacier changes over decades as well as globally, the WGI provides the most comprehensive data set so far. In 1995, the Global Land Ice Measurements from Space project was initiated, in close cooperation with NSIDC and WGMS, which aims at continuing the task of the WGI based on the analysis of multispectral Landsat TM/ETM+ and ASTER satellite scenes storing the full complement of the WGI-defined glacier characteristics (cf. Bishop *et al.* 2004, Kargel *et al.* 2005, Raup *et al.* 2007). A new ESA-funded project called GlobGlacier aims at making a major contribution to the current GLIMS and WGMS database (Paul *et al.* 2009).

Protocols and standards

Standards and guidelines for the compilation of an inventory of the global distribution of perennial ice based on aerial photographs and maps, i.e. for the WGI (WGMS 1989), can be found in UNESCO (1970; 1970/73), Müller *et al.* (1977), Müller (1978), and Scherler (1983). These standards have been revised and updated for satellite based inventories within GLIMS, and are described in Rau *et al.* (2005), the GLIMS Algorithm Working Group (2009), as well as in Raup and Khalsa (2007). Based on these standards, recommendations and requirements for satellite-based components of the cryospheric monitoring have been derived and published in GCOS (2006) and IGOS (2007). A comprehensive overview of the problems related to the data collection based on historic maps is given by Fountain *et al.* (2006).

The most relevant guidelines for glacier inventories based on aerial photography and maps are:

- Müller, F., Caflisch, T. and Müller, G. (eds.). 1977. Instructions for the compilation and assemblage of data for a world glacier inventory. IAHS(ICSU)/UNESCO report, Temporal Technical Secretariat for the World Glacier Inventory (TTS/WGI), ETH Zurich, Switzerland.
- Müller, F. (ed.). 1978. Instructions for the compilation and assemblage of data for a world glacier inventory; Supplement: Identification/ glacier number IAHS(ICSU)/UNEP/UNESCO report, Temporal Technical Secretariat for the World Glacier Inventory (TTS/WGI), ETH Zurich, Switzerland.
- Scherler, K. (ed.). 1983. Guidelines for preliminary glacier inventories. IAHS(ICSU)/UNEP/UNESCO report, Temporal Technical Secretariat for the World Glacier Inventory (TTS/WGI), ETH Zurich, Switzerland.
- UNESCO (1970): Perennial ice and snow masses – a

guide for compilation and assemblage of data for the World Glacier Inventory. Technical Papers in Hydrology No. 1.

The most relevant guidelines for glacier inventories mainly based on satellite images are:

- Bishop, M.P., Barry, R.G., Bush, A.B.G., Copeland, L., Dwyer, J.L., Fountain, A.G., Haeberli, W., Hall, D.K., Käab, A., Kargel, J.S., Molnia, B.F., Olsenholler, J.A., Paul, F., Raup, B.H., Shroder, J.F., Trabant, D.C., and Wessels, R. (2004): Global Land Ice Measurements from Space (GLIMS): Remote sensing and GIS investigations of the Earth's cryosphere. Geocarto International, 19 (2), 57-85.
- GLIMS Algorithm Working Group. (2009): GLIMS algorithm document.
- Rau, F., Mauz, F., Vogt, S., Khalsa, J.S., and Raup B. (2005): Illustrated GLIMS glacier classification manual. Glacier classification guidance for the GLIMS inventory. NSIDC: 36 pp.
- Raup, B.H., and Khalsa, J.S. (2007): GLIMS analysis tutorial. Draft, 20070522. 15 p.
- Raup, B.H., Käab, A., Kargel, J.S., Bishop, M.P., Hamilton, G., Lee, E., Paul, F., Rau, F., Soltesz, D., Khalsa, S.J.S., Beedle, M., and Helm, C. (2007): Remote Sensing and GIS technology in the Global Land Ice Measurements from Space (GLIMS) Project. Computers and Geosciences, 33, 104-125.
- Raup, B.H., Racoviteanu, A., Khalsa, S.J.S., Helm, C., Armstrong, R., and Arnaud, Y. (2007): The GLIMS Geospatial Glacier Database: a new tool for studying glacier change. Global and Planetary Change, 56, 101-110.

In addition, the IGOS Cryosphere Theme Report (IGOS 2007) identified the observation requirements for glaciers and ice caps as shown in Table 1. This overview is primarily guided by the requirements for satellite missions and parameters that could be assessed from space. However, it also underlines the importance of a continuation of *in situ* measurements to validate the space-borne data sets.

Parameter	C T	Measurement Range			Measurement Accuracy		Resolution				Comment / Principal Driver
							Spatial		Temporal		
	O	L	H	U	V	U	V	U	V	U	
Area	C				1	%	5	m	30	a	Airborne
	O				3	%	30	m	5	a	Landsat etc.
	T	0.01	5000	Km ²	3	%	50	m	5	a	Hi res. optical
	O	0.01	5000	Km ²	1	%	15	m	1	a	
Topography	O										Airborne
	C	o	8500	m sl.	5	m	100	m	5	a	For models
	T	o	8500	m sl.	0.1	m	30	m	1	a	Mass balance
Velocity	O				1	%	point		1	a	<i>In situ</i>
	C	o	10	Km/a	5	%	200	m	1	a	In SAR etc.
	T	o	10	Km/a	1	%	50	m	1	m	
Glacier dammed lakes					1	%	1	m	1	a	Airborne
		0.05	10	Km ²	3	%	50	m	1	m	SAR, hi res. optical
		0.01	10	Km ²	1	%	15	m	5	d	
Facies, snowline	C						point				<i>In situ</i>
	T			class	200	m	100	m	1	m	Position of boundary
	O			class	30	m	30	m	10	d	
Accumulation	C				5	%	point				<i>In situ</i>
	T	0.05	8	m	10	%	500	m	1	a	Ku-, X-SAR
	O	0.10	5	m	5	%	100	m	1	m	
Mass balance	C				0.10	m	point				<i>In situ</i>
	T	o	±5	m	0.20	m	500	m	1	m	Process model & SAR
	O	o	±5	m	0.05	m	100	m	1	a	
Ice thickness	C										<i>In situ</i>
Ice cores	C										v
	O										

Table 1. Summary of current/planned capabilities and requirements for glaciers and ice caps. Codes are as follows: C = current capability, T = threshold requirement (minimum necessary), O = objective requirement (target), L/H = low/high end of measurement range, U = unit, V = value. Source: IGOS (2007)

3.3 Integrative change assessments

The numerous length change series together with the positions of moraines give a rather good qualitative overview on the global and regional glacier changes since their Little Ice Age maximum extents; whereas the mass balance series provide quantitative measures of the ice loss since the late 1940s. However, the relatively few glacier mass balance series cannot truly represent the changes of the global ice cover. Many regions with large ice covers are strongly underrepresented in the dataset or are even lacking of any observations. As a consequence, the field measurements with a high temporal resolution (but limited in spatial coverage) must be complemented with remotely sensed decadal area and volume change assessments in order to get a representative view of the climate change impacts. In addition, numerical modelling is needed to bridge the gap between local process studies and coverage at the global scale, to link the glacier fluctuations to the climate forcing (e.g. Hoelzle *et al.* 2003, Oerlemans 2005), and to downscale GCM/RCM scenarios for the use in local process models. This strategy would then allow calculating the consequences for the hydrological system and sea level change.

3.4 Summary of requirements and gaps

Over the decades of glacier monitoring, several manuals and guidelines have been published describing the terminology and methodology to compile glacier inventories, mass balance and front variation measurements. These reference documents are listed and (mostly) made available from the WGMS Web site (www.wgms.ch/guidelines.html). Investigators should follow these guidelines when submitting their data. The guidelines for the production of a

glacier inventory based on aerial photography and maps related to the World Glacier Inventory (WGI database) have been updated and extended for the production of satellite imagery based inventories (GLIMS database). Recently, a working group of the IACS has been established to prepare an updated reference document on mass balance terminology and methods. Another working group is currently elaborating guidelines for the compilation of detailed glacier inventory data from digital sources.

Regarding *in situ* measurements, the least developed guidelines are those for carrying out glacier front variation measurements. Some important parameters such as reconstructed glacier fluctuations, ice temperature and ice thickness are not yet compiled and disseminated in a standardized manner. However, the major challenges of the present glacier monitoring network are not shortcomings in guidelines or methodologies but rather the availability of long-term observation series that are well distributed over the glacierized regions and the quantitative assessment of uncertainties and errors of the available data.

Methods and standards for the compilation of glacier inventories from remote sensing data (mainly optical) are well established (e.g. Paul *et al.* 2002). However, the completion of a global detailed glacier inventory is not yet achieved and repeat inventories for entire mountain ranges are only available for a few regions. The suitability of remote sensing and geo-informatics for the assessment of the representativeness of *in situ* observation series for the glacier cover of entire mountain ranges, e.g. by deriving glacier volume changes from differencing of digital terrain models, has been shown (Paul and Haeberli 2008). However, for better resolution and quality new global digital terrain models are required. A large number of experimental studies have used other remote sensing technologies, such as thermal and hyperspectral scanning, laser scanning, synthetic

aperture radar altimeters and interferometers, to derive additional glacier parameters (e.g. debris covered ice, mass balance, snow facies, ice velocities) but have not (yet) become operational (Kääb 2005).

Scientific modelling studies do not yet make systematic use of the available glacier datasets for linking the local process knowledge with global coverage and there is still a major spatio-temporal gap between global/regional climate models and local process models for sound analysis of future glacier changes and its impacts on global sea level rise, regional runoff and the local hazard situation.

4. Contributing networks and agencies

4.1 History of international glacier monitoring

Worldwide collection of information on ongoing glacier changes was initiated in 1894 with the foundation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland. Today, the WGMS continues to collect and publish standardised information on ongoing glacier changes. WGMS is a service of the International Association of Cryospheric Sciences of the International Union of Geodesy and Geophysics (IACS/IUGG) as well as of the Federation of Astronomical and Geophysical Data Analysis Services of the International Council for Science (FAGS, ICSU) and maintains a network of local investigators and national correspondents in all the countries involved in glacier monitoring. In collaboration with the NSIDC and GLIMS, the WGMS is in charge of the Global Terrestrial Network for Glaciers (GTN-G) within the Global Climate/Terrestrial Observing System (Haeberli *et al.* 2000, Haeberli 2004).

4.2 Global Terrestrial Network for Glaciers (GTN-G)

The WGMS has managed the GTN-G within the Global Climate/Terrestrial Observing Systems since its creation in 1998 (Haeberli *et al.* 2000). The GTN-G aims at combining (a) *in situ* observations with remotely sensed data, (b) process understanding with global coverage and (c) traditional measurements with new technologies by using an integrated and multi-level strategy (Haeberli 2004). GTN-G is designed to provide quantitative and comprehensive information in connection with questions about process understanding, change detection, model validation and environmental impacts in an interdisciplinary knowledge transfer to the scientific community as well as to policy-makers, the media and the public. A Global Hierarchical Observing Strategy (GHOST) was developed to bridge the gap in scale, logistics and resolution between detailed process studies at a few selected sites and global coverage at pixel resolution using techniques of remote sensing and geoinformatics. The following main steps or “tiers” are included:

Tier 1: *Multi-component system observation across environmental gradients.*

Primary emphasis is on spatial diversity at large (continental-type) scales or along elevation belts of high-mountain regions. Special attention should be given to long-term measurements. Some of the glaciers already observed (for instance, those in the American Cordilleras or in a profile from the Pyrenees through the Alps and Scandinavia to Svalbard) could later form part of Tier 1 observations along large-scale transects.

Tier 2: *Extensive glacier mass balance and flow studies within major climatic zones for improved process understanding and calibration of numerical models.*

Full parameterization of coupled numerical energy/mass balance and flow models is based on detailed observations that improve process understanding, sensitivity experiments and extrapolation to regions with less comprehensive measurements. Ideally, sites should be located near the centre of the range of environmental conditions of the zone which they are representing. The actual locations will depend more on existing infrastructure and logistical feasibility rather than on strict spatial guidelines, but there is a need to capture a broad range of climatic zones (such as tropical, subtropical, monsoon-type, mid-latitude maritime/continental, subpolar, polar). Ideally, Tier 2 is represented by at least one glacier in each major mountain range.

Tier 3: *Determination of regional glacier volume change within major mountain systems using cost-saving methodologies.*

There are numerous sites that reflect regional patterns of glacier mass change within major mountain systems, but they are not optimally distributed (Cogley and Adams 1998). Observations with a limited number of strategically selected index stakes (annual time resolution) combined with precision mapping at about decadal intervals (volume change of entire glaciers) for smaller ice bodies, or with laser altimetry/kinematic GPS (Arendt *et al.* 2002) for large glaciers constitute optimal possibilities for extending the information into remote areas of difficult access. Repeated mapping and altimetry alone provide valuable data at a lower time resolution (decades). Ideally, Tier 3 observation sites enclose approximately ten glaciers in each mountain range.

Tier 4: *Long-term observations of glacier length change data within major mountain ranges for assessing the representativity of mass balance and volume change measurements.*

At this level, spatial representativity is the highest priority. Locations should be based on

statistical considerations (Meier and Bahr 1996) concerning climate characteristics, size effects and dynamics (calving, surge, debris cover, etc.). Long-term observations of glacier length changes at a minimum of about ten sites within each of the important mountain ranges is recommended at annual to decadal frequencies. Remote sensing and geo-informatics provide the potential of calculating changes for hundreds or even thousands of glaciers in each mountain range at decadal intervals.

Tier 5: *Glacier inventories repeated at time intervals of a few decades by using satellite remote sensing.*

Continuous upgrading of preliminary inventories and repetition of detailed inventories using aerial photography or – in most cases – satellite imagery should make it possible to attain global coverage and to serve as a validation and input data set for climate models. The use of digital terrain information in combination with geo-informatics greatly facilitates automated procedures of image analysis, data processing and modelling/interpretation of newly available information (Kääb *et al.* 2002, Paul *et al.* 2002). Preparation of data products from satellite measurements must be based on a long-term programme of data acquisition, archiving, product generation, and quality control.

This integrated and multi-level strategy forms the base of the GTN-G observations. Tiers 2 and 4 mainly represent traditional (field based) methodologies which remain fundamentally important for deeper understanding of the involved processes, as training components in environment-related educational programmes and as unique demonstration objects for a wider public. Tiers 3 and 5 constitute wide-open doors for the large-scale application of new and existing technologies (remote sensing, modelling).

A network of about 100 glaciers representing Tiers 2 and 3 has been established. This step closely

corresponds to the data compilation published so far by the WGMS with the biennial Glacier Mass Balance Bulletin and also guarantees annual reporting in electronic form. A selected sample of 30 reference glaciers with continuous long-term measurements provides information on presently observed rates of change in glacier mass, corresponding acceleration trends and regional distribution patterns. Long-term changes in glacier length or volume must be used to assess the representativeness of the sample of values measured during a few decades with respect to the evolution at a global scale and during previous time periods. This can be done by (a) intercomparison between curves of cumulative glacier length change from geometrically similar glaciers, (b) application of continuity considerations for assumed step changes between steady-state conditions reached after the dynamic response time (Hoelzle *et al.* 2003), (c)

dynamic fitting of time-dependent flow models to present-day geometries and observed long-term length changes (e.g. Oerlemans *et al.* 1998), (d) analysis of time-lapse digital terrain models (e.g. Bauder *et al.* 2007), and (d) laser altimetry (e.g. Arendt *et al.* 2002). A paper by Haeberli *et al.* (2007) illustrates the implementation of this multi-level strategy using the example of the European Alps.

5. Available data

A spatio-temporal overview of the available data is given in Table 2 and Figures 1 & 2. A more comprehensive overview on the available datasets, the global glacier distribution and changes since the maximum extent of the Little Ice Age (LIA) is provided by WGMS (2008a).

Macroregion	Area	FRONT VARIATION								MASS BALANCE						
		No Ser	NoSer 21th	First RY	First SY	Last SY	AvTR	AvNo Obs	Ser Dens	No Ser	NoRef Ser	NoSer 21st	First SY	Last SY	AvNo Obs	Ser Dens
New Guinea	3	3	0	1936	1941	1990	46.3	4.7	1000.0	0	0	0				0.0
Africa	6	14	11	1893	1899	2004	71.4	6.1	2333.3	1	0	0	1979	1996	18.0	166.7
New Zealand	1160	99	70	1879	1892	2005	14.4	6.2	85.3	3	0	1	1959	2005	2.7	2.6
Scandinavia	2940	67	45	1896	1899	2005	53.2	30.2	22.8	39	8	23	1946	2005	16.3	13.3
Central Europe	3785	764	417	1730	1815	2005	65.1	35.3	201.8	43	10	29	1948	2005	19.6	11.4
South America	25500	160	49	1830	1888	2005	36.4	4.1	6.3	11	1	9	1976	2005	8.1	0.4
Northern Asia	59600	24	11	1833	1895	2005	55.2	14.1	0.4	14	3	5	1962	2005	13.5	0.2
Antarctica	77000	48	7	1882	1883	2004	30.4	2.8	0.6	1	0	1	2002	2005	4.0	0.0
Central Asia	114800	310	16	1850	1893	2005	21.5	4.5	2.7	35	2	6	1957	2005	13.1	0.3
North America	124000	221	15	1720	1885	2005	36.9	5.2	1.8	45	4	24	1953	2005	15.8	0.4
Arctic	275500	93	49	1840	1886	2005	52.4	30.5	0.3	34	2	20	1960	2005	12.6	0.1
Worldwide	684294	1803	690	1720	1815	2005	46.7	20.1	2.6	226	30	118	1946	2005	15.0	0.3

Notes:

NoSer: Number of series; NoSer 21th: number of series with last survey after 1999; FirstRY: first reference year; FirstSY: first survey year; LastSY: last survey year; AvTR: average time range per series; AvNoObs: average number of observations per series; SerDens: number of series per 1 000 square kilometre; NoRefSer: number of 'reference' mass balance series with continuous measurements since 1976.

Table 2. Estimated global and regional glacier coverage and available length change and mass balance data.
Source: WGMS (2008a)

5.1 *In situ*

The WGMS hosts an unprecedented dataset of information on spatial glacier distribution and changes over time which is readily available to the scientific community and the public. At present, the database contains about 36 000 front variation and 3 400 annual mass balance observations for 1 800 and 230 glaciers, respectively (WGMS 2008a).

5.2 Remote-sensing

At present the WGI database contains information for over 100 000 glaciers throughout the world with an overall area of about 240 000 km². This corresponds to about half of the estimated total number (160 000) and roughly one third of the estimated global ice cover (685 000 km²) related to glaciers and ice caps around the 1970s. The GLIMS glacier database

contains digital outlines of over 83 000 glaciers covering about 261 000 km², partly congruent with the ones in the WGI. Repeat inventories for glacier change assessments are only available for some individual regions, some countries and a few entire mountain ranges.

6. Further issues

6.1 Data set uncertainties

For more than a century, information on glacier changes and distribution have been collected worldwide and made freely available through a mainly scientific collaboration network. This is a great success and, at the same time, one of the reasons why the present monitoring network is unevenly distributed in comparison to the global ice coverage and consists of datasets with large in-homogeneities

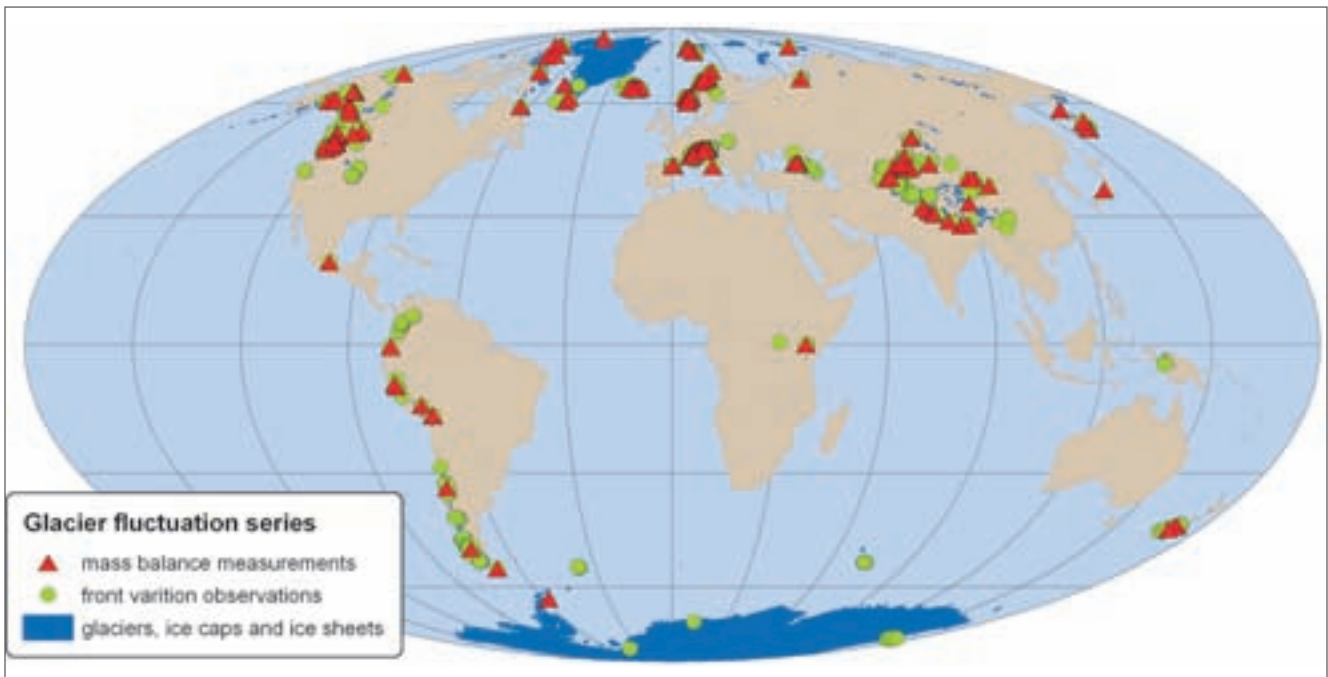


Fig. 1: Global distribution of available glacier fluctuation data. The estimated global glacier distribution is shown with locations of glacier front variation and mass balance measurements. Data source: locations of glacier fluctuation series provided by the WGMS, Zurich, Switzerland; background glacier cover is based on the glacier layer of ESRI's Digital Chart of the World, provided by the NSIDC, Boulder, USA

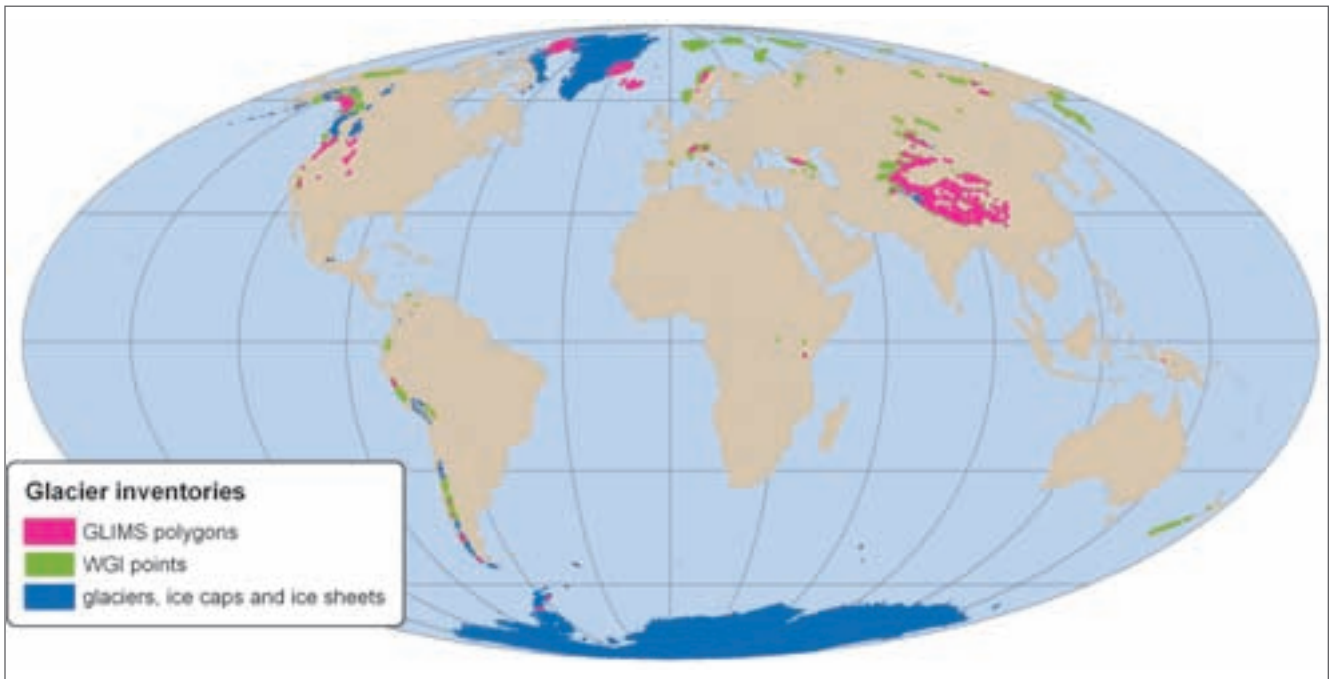


Fig. 2: Global distribution of available glacier inventory data. The estimated global glacier distribution is shown with locations of glacier point of the WGMS and glacier outlines of the GLIMS databases. Data source: WGI data provided by the WGMS, Zurich, Switzerland; GLIMS data provided by the GLIMS at NSIDC, Boulder, USA; background glacier cover is based on the glacier layer of ESRI's Digital Chart of the World, provided by the NSIDC, Boulder, USA

in measurement techniques. Given the present state of knowledge, the manifold sources of errors, and the often missing meta-information, it is not possible to exactly quantify the overall error of available mass balance, length change, and inventory data (e.g. Kaser *et al.* 2006, Raup *et al.* 2007, Zemp *et al.* 2009). In order to reduce, better understand, and quantify the uncertainties, we recommend to strictly adhere to the given standards, systematically validate and calibrate the field observations with decadal changes as assessed from geodetic methods, and to provide also the corresponding meta-information. Furthermore, systematic use of remote sensing and geo-informatics is required for the assessment of the representativeness of the available field observations for their mountain range and for the extrapolation to regions without *in situ* observations.

6.2 Operations and funding

For many decades, the WGMS has been the principal mechanism for assembling and reporting on glacier fluctuations at the global level and in a standardized manner. At present, the service runs on a three-year bridge funding (2007–2009) from the Swiss National Science Foundation and the Swiss Federal Office for the Environment. From January 2010, the WGMS will be financed in the long run by the Swiss GCOS Office at the Federal Office of Meteorology and Climatology MeteoSwiss, based on a decision by the Federal Council of Switzerland in June 2008. The hosting and maintenance of the GLIMS database at the NSIDC is currently funded through research grants from the US National Aeronautics and Space Administration's Distributed Active Archive Center (NASA's DAAC).

7. Conclusions

Internationally coordinated glacier observations started already back in 1894 and have now a tradition of more than a century. In addition to the three primary glacier variables (specific mass balance, front variation, area), several other parameters have been monitored to understand the glacier distribution, their behaviour and related processes. The measurements are integrated in a tiered observation strategy that combines *in situ* observations with remotely sensed data, process understanding with global coverage, and traditional measurements with new technologies. The WGMS, in cooperation with GLIMS and the NSIDC, is the principal mechanism for assembling and reporting on glacier changes at the global level and in a standardized manner. However, the continued operation of these services requires a long-term financial commitment to support this essential activity.

Under present climate change scenarios (cf. IPCC 2007), the ongoing rapid and perhaps accelerating trend of worldwide glacier shrinkage, on the century time-scale, is most likely of a non-periodic nature and may lead to the deglaciation of large parts of many mountain ranges within the coming decades (e.g. Zemp *et al.* 2007b, Nesje *et al.* 2008). To keep track of these fast environmental changes and to assess corresponding impacts on landscape evolution, fresh water supply and natural hazards, monitoring strategies will have to make use of the rapidly developing new technologies (remote sensing and geo-informatics) and relate them to the more traditional methods (Paul *et al.* 2007). Such challenges of historical dimensions, both with respect to changes in nature and science, can only be faced by a well organized and funded international monitoring organization.

8. Recommendations

1. Make *in situ* and remotely sensed glacier measurements with related meta-data readily available according to the international standards and guidelines.
2. Complete the compilation of a detailed worldwide inventory of glaciers and ice caps (with two-dimensional outlines) for a certain point in time, or at least cover all mountain ranges with relevant ice masses and a major percentage of the overall glacier area.
3. Assess global glacier changes at time intervals of about ten years within key regions where the surface land ice cover is relevant for issues related to climate change, hydrology and sea level change. This task requires long-term continuation of Landsat/ASTER type satellite missions, providing data at favourable costs, and a more formally established glacier monitoring by the GLIMS community.
4. Continuation of long-term glacier fluctuation series (i.e. mass balance and front variation). Decadal changes of glacier volume/thickness and length from geodetic and photogrammetric methods should be used to verify these annual *in situ* observations, and to extent their representativeness in space and back in time.
5. Strengthen the current monitoring network with additional observation series (i.e. mass balance and front variation) and re-initiation of interrupted long-term series in North and South America, Central and Northern Asia, Africa, New Zealand and around the two ice sheets in order to reduce the present bias towards observations in the Northern Hemisphere and in particular Europe.

6. Turn more attention to the understanding and quantification of the uncertainties of the available datasets.
7. Make systematic use of remote sensing and geoinformatics to assess the representativeness of the available *in situ* observation series for the glacier cover of their mountain ranges.
8. Encourage the modelling community to use the available datasets for linking the local process studies with global coverage, glacier fluctuations to climatic forcing and to bridge the gap between global/regional climate models and local glacier models to better assess future glacier changes and its impacts (e.g. sea level rise, runoff, hazards).
9. Strengthen the organizational structure and cooperation of the organisations involved in the international glacier monitoring (WGMS, NSIDC, and GLIMS) within GTN-G.
10. As a matter of priority, the governments and international agencies concerned with climate change impacts need to identify funds required for the maintenance of long-term observation series and for the continuing operation of the services running the GTN-G, as the main mechanism for assembling and publishing information on glacier distribution and changes around the world.

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Web Sites

Federation of Astronomical and Geophysical Data
Analysis Services (FAGS):

www.icsu-fags.org/

Global Climate Observing System (GCOS):

www.wmo.ch/pages/prog/gcos/

GlobGlacier project:

www.globglacier.ch

Global Land Ice Measurements from Space (GLIMS):

www.glims.org

Global Terrestrial Network for Glaciers (GTN-G):

www.gtn-g.org

Global Terrestrial Observing System (GTOS):

www.fao.org/gtos/

International Association of Cryospheric Sciences
(IACS):

www.cryosphericciences.org/

United Nations Educational, Scientific and Cultural
Organization (UNESCO):

www.unesco.org/

United Nations Environment Programme (UNEP):

www.unep.org/

US National Snow and Ice Data Center (NSIDC):

www.nsidc.org

World Glacier Monitoring Service (WGMS):

www.wgms.ch

World Meteorological Organization (WMO):

www.wmo.ch



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