The Monitoring of Glaciers at Local, Mountain, and Global Scale

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Excerpt from the introductory discourse of
"Les Variations périodiques des Glaciers" by Forel (1895).

L'œuvre que la Commission internationale des glaciers a devant elle est grande et intéressante ; elle est difficile. Abordons-la avec calme, courage et dévouement. Pour commencer, traitons le problème le plus simplement possible et bornons-nous à récolter tous les faits historiques qui peuvent nous faire connaître les variations glaciaires dans le passé [1], et à instituer des observations qui nous les fassent connaître dans le présent et dans l'avenir. Quand cette base aura été solidement établie, les questions subsidiaires de cause, d'effet, de relations avec d'autres phénomènes, les questions théoriques, etc., se présenteront tout naturellement à nos études, et nous, ou nos successeurs, les traiterons à mesure qu'elles se développeront devant nous.

Summary

Information about ongoing glacier changes was already being collected internationally as early as 1894. In the beginning, the focus was on compiling and publishing findings relating to glacier front variations, in the hope that long-term glacier monitoring would give insight into processes affecting the formation of the *Ice Ages*. Since then, the datasets and goals of international glacier monitoring have evolved and multiplied. Glaciers have become the icon of global warming, which has resulted in an increasing demand for data and information about their global and regional distribution and changes. Modern monitoring strategies have been designed to provide quantitative and understandable information in connection with questions about process understanding, change detection, model calibration and validation, as well as environmental impacts. As such, monitoring can be regarded as the data backbone for scientific research. However, in spite of the early start of internationally coordinated glacier monitoring and its contemporaneous evolution within the glaciological sciences, the relevance of long-term glacier monitoring has not yet been fully acknowledged by the scientific community and funding agencies.

It is to fill this gap in understanding that the present work undertakes to demonstrate the relevance of glacier monitoring, and its ability to complement scientific studies, on a local, mountain, and global scale. Based on 14 publications with essential contributions by this author, this work provides an overview of the historical background and present context of glacier monitoring, and the relevant organizations, strategies, and datasets. In the thematic main part, the methodological implementation of these concepts is presented, including exemplary results at different spatio-temporal scales integrating in-situ and remote sensing measurements, and numerical modeling. This is followed by a first effort to measure the relevance of internationally coordinated glacier monitoring. In this way, the present work provides a comprehensive summary of monitoring concepts, the results from recent distribution and glacier change studies, and an outlook on the corresponding key tasks for the coming decade(s).

The internationally coordinated monitoring efforts over more than a century have resulted in an unprecedented dataset of information about spatial glacier distribution and changes over time. These datasets are readily available and include reconstructed glacier changes extending back into the *Little Ice Age* and the *Holocene*, direct observations of annual front variation dating back to the late 19th century, six decades of annual and seasonal mass balance measurements, and a preliminary world glacier inventory for the 1970s, based mainly on aerial photographs and maps, with detailed information on more than 100,000 glaciers. This latter inventory task continues through the present day, now based mainly on satellite images. These datasets document that the retreat from the *Little Ice Age* moraines is a worldwide and centennial trend showing increasing ice loss since the mid 1980s, with intermittent periods of glacier re-advances at regional and decadal scale. When looking at individual fluctuation series, one finds a high rate of variability and sometimes widely contrasting behavior of neighboring ice bodies. Reviewing the extensive literature available on process understanding and numerical modeling of glaciers, it becomes evident that, given current climate change scenarios, the ongoing trend of worldwide and rapid ice loss may lead to the deglaciation of large sectors of many mountain ranges during the present century. This will most probably trigger secondary impacts on global sea level rise, regional hydrologic regimes and landscape evolution, and local hazard situations beyond known historic and *Holocene* experience. Such rapid environmental changes require that the international glacier monitoring efforts make use of swiftly developing new technologies, such as remote sensing and geo-informatics, and relate them to the more traditional field observations, in order to tackle the challenges of the 21st century in a more effective way.

Contents

Part A: Overview

Part B: Publications

The present work is based on 14 publications. They are arranged according to thematic considerations, and peer-reviewed articles are marked by *. A complete list of publications by the author is given on his website: http://www.geo.uzh.ch/~mzemp/

P01* **Zemp, M.**, Armstrong, R., Gärtner-Roer, I., Haeberli, W., Hoelzle, M., Kääb, A., Kargel, J.S., Singh Khalsa S.J., Paul, F. & Raup, B. (accepted). Chapter 1: **Global glacier monitoring - a long-term task integrating in-situ observations and remote sensing.** In: Kargel, J.S., Bishop, M.P., Kääb, A. & Raup, B.H. (eds.): Global Land Ice Measurements from Space. Satellite mulitspectral imaging of glaciers. Praxis-Spring.

P02 WGMS (2008b). **Fluctuations of Glaciers 2000-2005** (Vol. IX). Haeberli, W., **Zemp**, **M.**, Kääb, A., Paul, F. & Hoelzle, M. (eds.), ICSU (FAGS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland, 266 pp.

P03 WGMS (2009). **Glacier Mass Balance Bulletin No. 10 (2006–2007)**. Haeberli, W., Gärtner-Roer, I., Hoelzle, M., Paul, F. & **Zemp, M.** (eds.), ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 96 pp.

P04* **Zemp, M.**, Zumbühl, H.J., Nussbaumer, S.U., Masiokas, M.H., Espizua, L.E. and Pitte, P. (subm.). **Extending glacier monitoring into the Little Ice Age and beyond.** PAGES news, 19(2).

P05* Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A.A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Möller, M., Nicholson, L. & **Zemp, M.** (2011). **Glossary of Glacier Mass Balance and Related Terms**. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris.

P06* Paul, F., Barry, R.G., Gogley, J.G., Frey, H., Haeberli, W., Ohmura, A., Ommanney, S.C.L., Raup, B., Rivera, A. & **Zemp, M.** (2009). **Recommendations for the compilation of glacier inventory data from digital sources.** Annals of Glaciology, 50(53), 119-126.

P07* Koblet, T, Gärtner-Roer, I., **Zemp, M.**, Jansson, P., Thee, P., Haeberli, W. & Holmlund, P. (2010). **Re-analysis of multi-temporal aerial images of Storglaciären, Sweden (1959-99) - Part 1: Determination of length, area, and volume changes.** The Cryosphere, 4, 333-343.

P08* **Zemp, M.**, Jansson, P., Holmlund, P., Gärtner-Roer, I., Koblet, T., Thee, P. & Haeberli, W. (2010). **Re-analysis of multi-temporal aerial images of Storglaciären, Sweden (1959-99) - Part 2: Comparison of glaciological and volumetric mass balances.** The Cryosphere, 4, 345-357.

P09* **Zemp, M.**, Paul, F., Hoelzle, M. & Haeberli, W. (2008), **Glacier fluctuations in the European Alps 1850–2000: an overview and spatio-temporal analysis of available data.** In: Orlove, B., Wiegandt, E. & Luckman, B. (eds.): The darkening peaks: Glacial retreat in scientific and social context. University of California Press, 152-167.

P10* **Zemp, M.**, Hoelzle, M. & Haeberli, W. (2007). **Distributed modeling of the regional climatic equilibrium line altitude of glaciers in the European Alps.** Global and Planetary Change, 56, 83-100, doi:10.1016/j.gloplacha.2006.07.002.

P11* **Zemp, M.**, Haeberli, W., Hoelzle, M. & Paul, F. (2006). **Alpine glaciers to disappear within decades?** Geophysical Research Letters, 33, L13504, doi:10.1029/2006GL026319.

P12 **Zemp, M.**, Andreassen, L.M., Braun, L., Chueca, J., Fischer, A., Hagen, J.O., Hoelzle, M., Jansson, P., Kohler, J., Meneghel, M., Stastny, P. & Vincent, C. (2010). **Glacier and Ice Caps**. In: Voigt, T., Füssel, H.-M., Gärtner-Roer, I., Huggel, C., Marty, C. & **Zemp, M.** (eds.). **Impacts of climate change on snow, ice, and permafrost in Europe: Observed trends, future projections, and socio-economic relevance.** European Topic Centre on Air and Climate Change, Technical Paper, 2010 (13), 46-65.

P13* WGMS (2008a). **Global Glacier Changes: facts and figures. Zemp, M.**, Roer, I., Kääb, A., Hoelzle, M., Paul, F. & Haeberli, W. (eds.), UNEP, World Glacier Monitoring Service, Zurich, Switzerland: 88 pp.

P14* **Zemp, M.**, Hoelzle, M. & Haeberli, W. (2009). **Six decades of glacier mass balance observations - a review of the worldwide monitoring network.** Annals of Glaciology, 50(50), 101-111.

List of Abbreviations

CEOS	Committee on Earth Observation Satellites
CIG	Commission Internationale des Glacier
CliC	WCRP's Climate and Cryosphere project
COP	Conference of the Parties of the UNFCCC
DEM	Digital Elevation Model
ECV	Essential Climate Variable
ESA	European Space Agency
FAGS	ICSU's Federation of Astronomical and Geophysical Data Analysis Services
FAO	Food and Agriculture Organization of the UN
GCOS	Global Climate Observing System
GEOSS	Global Earth Observation System of Systems
GHOST	Global Hierarchical Observing Strategy
GLIMS	Global Land Ice Measurements from Space
GOOS	Global Ocean Observing System
GT-Net	Global Terrestrial Network
GTN-G	Global Terrestrial Network for Glaciers
GTN-H	Global Terrestrial Network for Hydrology
GTN-P	Global Terrestrial Network for Permafrost
GTN-R	Global Terrestrial Network for River Discharge
GTOS	Global Terrestrial Observing System
IACS	International Association of Cryospheric Sciences
IASH	International Association of Scientific Hydrology
IAHS	International Association of Hydrological Sciences
ICSI	International Commission on Snow and Ice
ICSU	International Council for Science
IHD	International Hydrological Decade
IHP	UNESCO's International Hydrological Program
IPCC	Intergovernmental Panel on Climate Change
IUGG	International Union of Geodesy and Geophysics
LIA	Little Ice Age
NSIDC	US National Snow and Ice Data Center in Boulder
PSFG	Permanent Service on the Fluctuations of Glaciers
TOPC	Terrestrial Observation Panel for Climate of GCOS and GTOS
TTS/WGI	Temporal Technical Secretariat for the World Glacier Inventory
UN	United Nations
UNESCO	UN Educational, Scientific and Cultural Organization
UNFCCC	UN Framework Convention on Climate Change
WCP	WMO's World Climate Program
WCRP	WMO's World Climate Research Program
WDS	ICSU's World Data System
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service
WMO	World Meteorological Organization

1 About this Work

1.1 Motivation

Glaciers are among the most fascinating elements of nature, an important freshwater resource but also an important contributor to the present sea level rise and a potential cause of serious natural hazards. Because they are close to the melting point and react strongly to small changes in climate, glaciers provide some of the clearest evidence of climate change and constitute key variables for early-detection strategies in global climate-related observations (GCOS, 2004; GTOS, 2008). Throughout the history of modern science, glaciers have not only been a source of fascination but also a key element in discussions about Earth evolution and climate change. The discovery of the Ice Age in the late 18th and the 19th century significantly contributed to the understanding of the evolutionary development of the Earth; it also demonstrated the possibility of important climate changes involving dramatic environmental effects at global scale (Forel, 1895). When systematic glacier observation began in the late 19th century, it was hoped that long-term glacier monitoring would give insight into processes affecting the formation of the Ice Ages (Agassiz, 1840). Since then, the goals of the international glacier monitoring have evolved and multiplied (Haeberli, 2004). Modern monitoring strategies are designed to provide quantitative and understandable information in connection with questions about process understanding, change detection, model calibration and validation as well as environmental impacts in a transdisciplinary knowledge transfer to the scientific community as well as to policymakers, the media and the public (WGMS, 2008a). As such, monitoring can be regarded as the data backbone for scientific research. However, in spite of the early start of internationally coordinated glacier monitoring and its contemporaneous evolution within the glaciological sciences, the relevance of glacier monitoring has repeatedly been questioned by, and lived in the shadow of its scientific community (Haeberli, 2008). Still today, the importance of long-term environmental monitoring is widely neglected by the scientific community and funding agencies, which is clearly reflected by the lack of implementation of the climate-related observation network in the terrestrial domain in support of the *United Nations Framework Convention on Climate Change* (UNFCCC; cf. GCOS 2010).

1.2 Objectives

The present work aims to provide a thorough overview of glacier monitoring, while demonstrating both the relevance of environmental monitoring and its ability to perfectly complement and complete (the purely) scientific endeavors in this field. To this end, the theoretical concept of internationally coordinated glacier monitoring is reviewed, set in context and complemented by the most important results from published contributions by the author. The main tasks are to:

- give a brief summary of the context of international monitoring of the cryosphere,
- provide a conceptual overview of international glacier monitoring including historical development, present organizations, strategies, and datasets,
- present and discuss the methodological implementation of these concepts,
- present and discuss the most significant results from glacier monitoring at local, mountain, and global scale,
- demonstrate the relevance of glacier monitoring to its own network, the scientific community, non- and governmental agencies, the media, and the wider public, and to
- summarize the present state and challenges of international glacier monitoring and provide an outlook on the key tasks for the coming decade(s).

1.3 Structure of the Work

The present work is arranged in two parts (see Figure 1.1).

Part A provides an overview of the monitoring of glaciers and consists of six major chapters: this introductory remark constitutes Chapter 1 covering the motivation, objectives, and structure of the work. Chapter 2 provides an introduction on the definition and spatio-temporal distribution of the cryosphere, explains the difference and interplay between science and monitoring, and elaborates the historic background of the monitoring of the cryosphere as part of the global climate-related observation system. Chapter 3 further details the background of internationally coordinated glacier monitoring, including summaries from six publications on its historical evolution, recent data reports, extension of its database, and new guidelines and standards. Thematically, the main part of this work is found in Chapter 4 which consists of summaries from eight publications which sum up the monitoring results of glacier distribution at local, mountain, and global scale, while integrating in-situ and remote sensing observations, numerical modeling, and reviews of the related scientific literature. Chapter 5 is a first attempt to discuss and estimate the relevance of the internationally coordinated glacier monitoring, followed by general conclusions and perspectives in Chapter 6.

Part B contains a full version of the 14 publications which comprise the main scientific work. Of these, the present author was the main contributor for nine of them, and played a significant role in the publication of the remaining five.

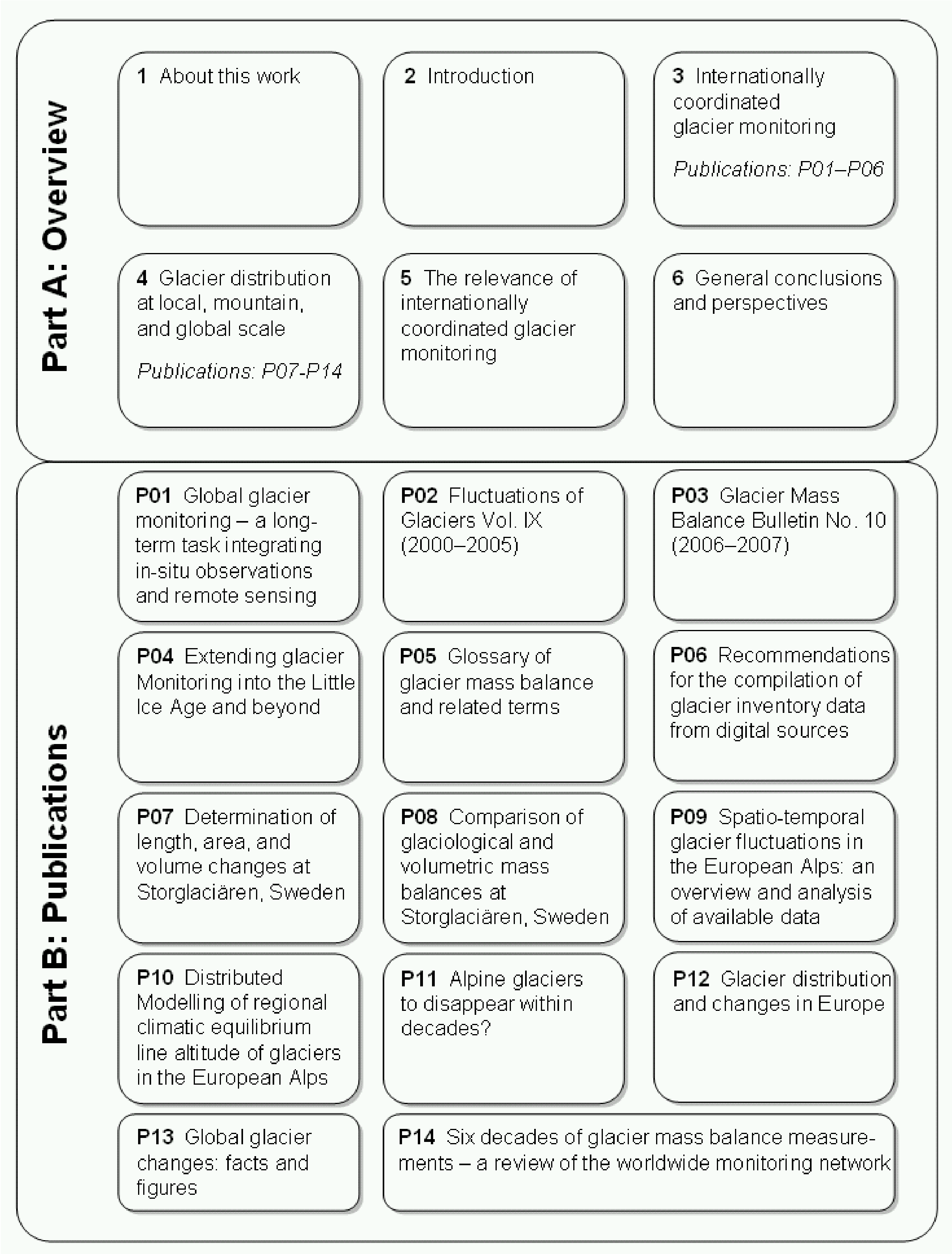

Figure 1.1: Schematic structure of the work, showing the contents of the two main parts, Overview and Publications.

2 Introduction

2.1 The Cryosphere: Definition and Spatio-temporal Distribution

The term cryosphere derives from the Greek word *kryo* for cold and stands for one of the Earth's spheres consisting of different components of frozen elements including snow, river and lake ice, sea ice, glaciers and ice caps, ice shelves and ice sheets, and frozen ground (Figure 2.1). These cryospheric components can be categorized as seasonal and perennial ice, surface and subsurface ice, as well as in ice in the sea, in rivers and lakes, and on land (Lemke et al., 2007). When referring to perennial surface ice on land, one usually differentiates between glaciers and ice caps, and ice sheets.

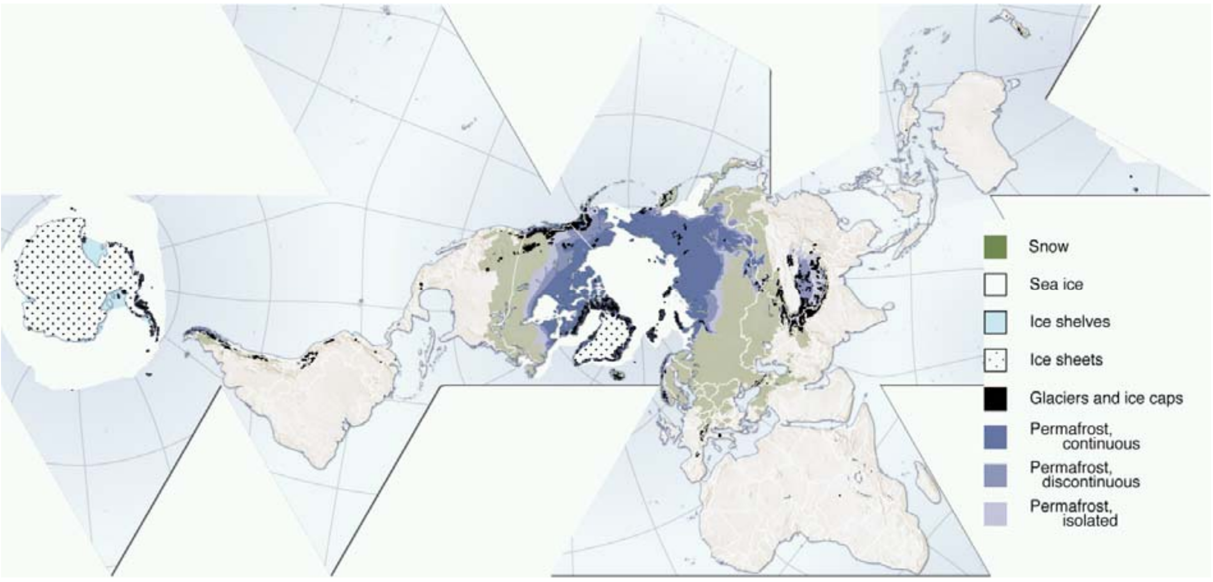

Figure 2.1: Global distribution of the cryosphere. Note that for snow and sea ice the seasonal maximum distribution is shown for both hemispheres. Source: UNEP (2007).

The relevance of the cryosphere for climate variability and change is based on physical properties, such as its high surface reflectivity (albedo) and the latent heat associated with phase changes, which have a strong impact on the surface energy balance (Lemke et al., 2007). The presence (absence) of snow or ice in Polar Regions is associated with an increased (decreased) meridional temperature difference, which affects winds and ocean currents. Because of the positive temperature-ice albedo feedback, some cryospheric components act to amplify both changes and variability. Elements of the cryosphere are found at all latitudes, enabling a near-global assessment of cryosphere-related climate changes. There are fundamental differences in time scales and processes involved between the different components (Figure 2.2).

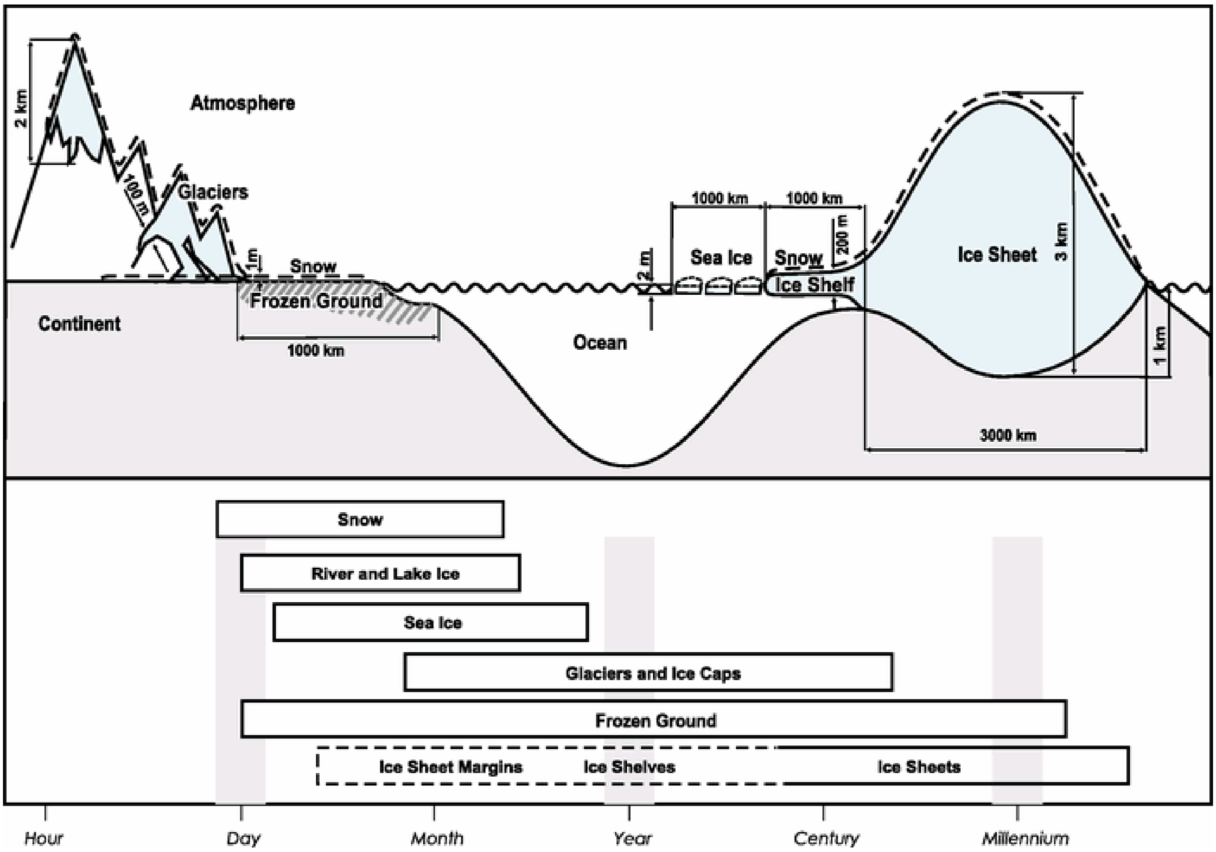

Figure 2.2: Components of the cryosphere and their time scales. Source: Figure 4.1 from Lemke et al. (2007).

Due to the large volumes and areas, the (presently existing) two continental ice sheets in Greenland and Antarctica actively influence the global weather and climate over time scales of months to millennia. Glaciers and ice caps, with their much smaller volumes and areas, react to climatic forcing at typical time scales from years to centuries. Also, lake and river ice is a good climate indicator at seasonal timescale. Snow and sea ice are both of small volumes but of large seasonal extents and, hence, interact strongly – via albedo feedbacks - with the climate system. On a larger time scale, there is also an important interaction between frozen ground and the global climate through large amounts of methane stored in lowland permafrost. Good overviews on the state of knowledge concerning all cryospheric components can be found in IGOS (2007), Lemke et al. (2007), and UNEP (2007), with a recent update of the latter by Koç et al. (2009).

2.2 Science versus Monitoring

'Science' derives from the Latin noun *scientia* for knowledge and stands for 'the intellectual and practical activity encompassing the systematic study of the structure and behavior of the physical and natural world through observation and experiment' (OxfordDictionaries, 2010a). 'Natural sciences' refers to hypothesis-driven research which is typically project-based and mainly financed through scientific funding agencies. 'Monitoring' derives from the Latin verb *monere* for 'to warn' and stands for 'observing, checking, or keeping a continuous record of something' (OxfordDictionaries, 2010b). Environmental monitoring is the long-term surveillance of phenomena with the aim of detecting changes and is mostly financed through national non-scientific agencies. Whereas science is primarily judged according to the novelty of its results, the outcome of monitoring needs first of all to be relevant, feasible, and understandable. Therefore, monitoring is a permanent operational task based on established methodology, whereas a scientific project has a typical duration of three to six years and often includes innovative testing of new methods and techniques. As such, scientists are presently (i.e., in 2011) about to draft their papers for on-time submission to academic journals in order to be cited in the fifth assessment report of the *Intergovernmental Panel on Climate Change* (IPCC; relevant deadline for the status 'submitted' is end of July 2012), whereas the international monitoring organizations are already laying the (data) foundation for the assessment report(s) beyond this fifth report.

Ideally, monitoring provides standardized, long-term, and high-quality observation series as the fundamental basis for scientific studies, and assures the reproducibility of the scientific results through the continuing availability of these basic datasets. Draggan and Guinasso (2010) state the central argument for environmental monitoring in a single sentence: "You cannot recognize, understand, improve or maintain what you do not or cannot measure." As a consequence, climate-related science should be based on observation series that are longer than the standard averaging period, which is usually 30 years. This can be demonstrated nicely with the cumulative average mass balance series from nine Alpine glaciers with continuous annual observations since 1967 and earlier (Figure 2.3). The climatic trend (partly) driving the glacier changes can be detected only by means of a long-term monitoring program. Observations within the duration of typical scientific projects are too short for the detection of climatic trends and related extrapolation might even lead to wrong results.

Figure 2.3: Cumulative mass balance of nine Alpine glaciers with long-term continuous measurement series. Linear trends are given for two subperiods of six years. Data source: WGMS.

2.3 Monitoring of the Cryosphere as Part of the Global Climate-Related Observation Systems

2.3.1 World Climate Conferences, the Intergovernmental Panel on Climate Change, and the United Nations Framework Convention on Climate Change

The series of *World Climate Conferences*, organized by the *World Meteorological Organization* (WMO), can be regarded as a starting point for putting the climate change issue on the political agenda. The first conference was held in 1979 in Geneva, Switzerland, and was one of the first major international meetings on climate change. This mainly scientific conference led to the establishment of WMO's *World Climate Program* (WCP) and *World Climate Research Program* (WCRP), and to the creation of the IPCC by WMO and UNEP in 1988 (UN, 1988). The second conference was organized jointly by WMO and UNEP in 1990, again in Geneva, and was somewhat more political. The main tasks were to review the WCP and to discuss the results of the IPCC first assessment report (IPCC 1990), and resulted in a call for the elaboration of a framework treaty on climate change and the necessary protocols (UN, 1993). Based on this call for action, the UNFCCC was established in 1992 in Rio de Janeiro, Brazil, as the basis for a global response to the climate change issue. Since 1995, the parties of the Convention have met annually in the *Conference of the Parties* (COP) to assess progress in dealing with climate change. In 1997, the *Convention* was complemented by the *Kyoto Protocol* – to which the IPCC second assessment report (IPCC, 1996) provided key input – in which 37 industrialized countries and the European Community have committed to reducing their greenhouse gas emissions by an average of five percent by 2012 against 1990 levels (UN, 1998). The IPCC third and fourth assessment report further consolidated the state of knowledge on climate change and its anthropogenic contribution (IPCC 2001; 2007). The *Kyoto Protocol* entered into force in 2005 and is generally seen as an important first step towards a truly global emission reduction regime to stabilize greenhouse gas emissions, that also provides the essential frame of reference for any future international agreement on climate change. By the end of the first commitment period of the *Kyoto Protocol* in 2012, a new international framework needs to have been negotiated and ratified in order to continue this process. The third, and so far latest, *World Climate Conference* was held in Geneva in 2009, and proposed the establishment of a *Global Framework for Climate Services* to develop an interface between the providers and users of climate services (WMO, 2009).

2.3.2 Global Observing Systems, Essential Climate Variables, and Global Terrestrial Networks

The second *World Climate Conference* in 1990 called for the urgent establishment of coordinated climate system monitoring (UN, 1993). As a consequence, a global observation system was established under the co-sponsorship of UN's *Food and Agriculture Organization* (FAO), the *International Council for Science* (ICSU), UNEP, *United Nations Educational, Scientific and Cultural Organization* (UNESCO), and of the *World Meteorological Organization* (WMO) and consists of the following three components (acronym and year of initiation): *Global Climate Observing System* (GCOS, in 1992), *Global Ocean Observing System* (GOOS, in 1995), and *Global Terrestrial Observing System* (GTOS, in 1996). The three components are: permanent global systems for observations, modeling, and the analysis of variables describing the state of the climate, the oceans, and the terrestrial ecosystems. They all aim at setting up an international framework that coordinates operational efforts of individuals, national and international organizations, institutions and agencies in providing reliable in-situ and remotely sensed observations of the corresponding systems. In this way, the space-based components are coordinated by the *Committee on Earth Observation Satellites* (CEOS) which was established in 1984 and is run by international and national organizations responsible for civil space-borne Earth observations programs (CEOS, 2010). In addition, the three systems, GCOS, GTOS, and GOOS, constitute the observation components of the *Global Earth Observation System of Systems* (GEOSS; see Figure 2.4). GEOSS was launched in response to calls for action by the 2002 *World Summit on Sustainable Development* and by the *Group of Eight* leading industrialized countries and envisages tapping the full potential of Earth observations to support decision-making in the nine 'societal benefit areas' of disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity (GEO, 2005).

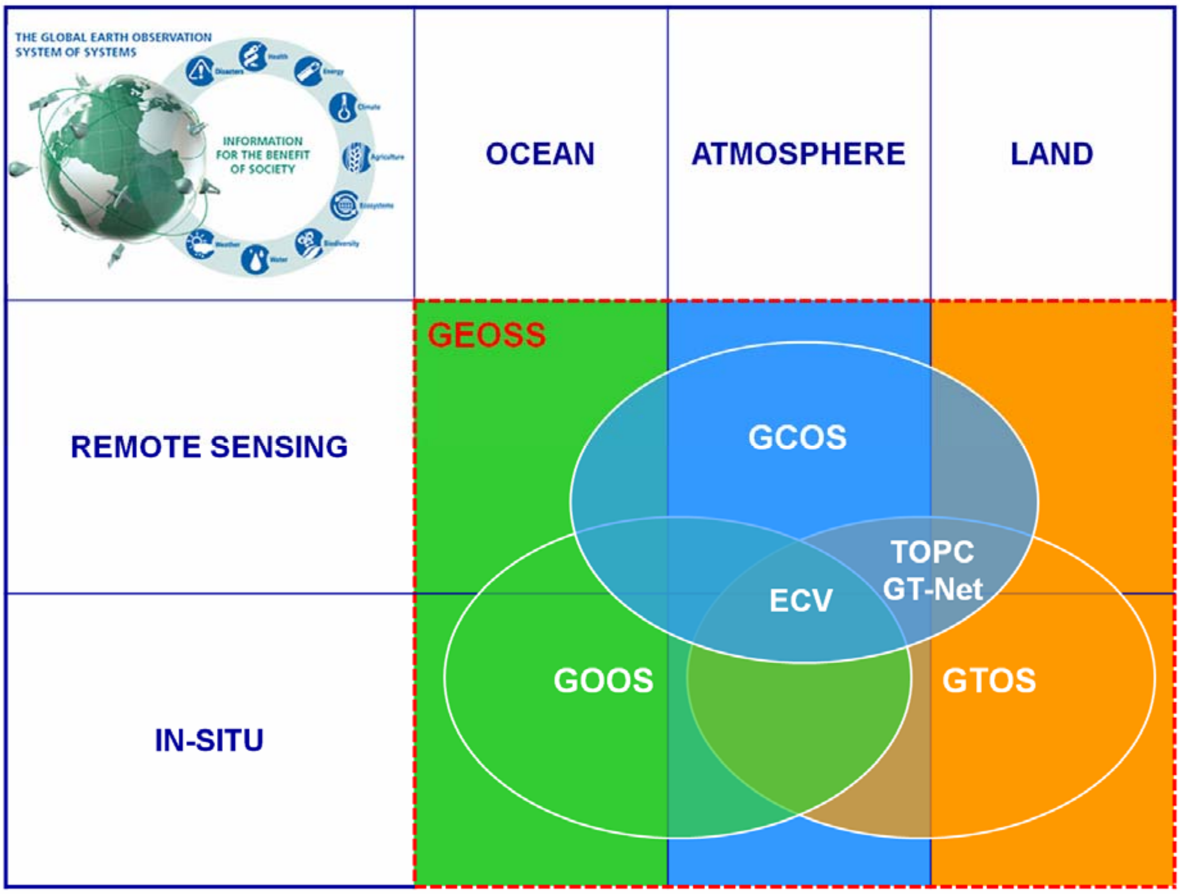

Figure 2.4: Schematic overview showing the observational and spatial domains of the *Global Ocean, Climate and Terrestrial Observation Systems* (GOOS, GCOS, GTOS) as part of the *Global Earth Observation System of Systems* (GEOSS).

As a basic requirement in support of the work of the UNFCCC and the IPCC, the global observation systems defined a set of *Essential Climate Variables* (ECVs) in all three domains which are technically and economically feasible for systematic observation (GCOS 2004). In 2010, an initial set of ECVs and a corresponding implementation plan were updated to include 50 ECVs and 138 Actions in order to provide countries with the information needed to understand, predict, and manage their response to climate and climate change over the 21st century and beyond (GCOS, 2010). The updated matrix of ECVs includes the majority of cryospheric components, notably sea ice in the ocean domains as well as snow cover, glaciers and ice caps, permafrost and seasonally frozen ground, and ice sheets in the terrestrial domain (see Table 2.1).

Domain	GCOS Essential Climate Variables
Atmospheric (over land, sea, and ice)	**Surface**: air temperature, wind speed and direction, water vapor, pressure, surface radiation budget. **Upper-air**: temperature, wind speed and direction, water vapor, cloud properties, earth radiation budget (including solar irradiance). **Composition**: carbon dioxide, methane, and other long-lasting greenhouse gases, ozone and aerosols, supported by their precursors.
Oceanic	**Surface**: sea-surface temperature, sea-surface salinity, sea level, sea state, ***sea ice***, surface current, ocean color, carbon dioxide partial pressure, ocean acidity, phytoplankton. **Subsurface**: temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers.
Terrestrial	River discharge, water use, groundwater, lakes, ***snow cover***, ***glaciers and ice caps***, ***ice sheets***, ***permafrost***, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, soil moisture.

Table 2.1: Matrix showing the 50 ECVs that are selected for their technical and economical feasibility for systematic observation, and as required in support of the UNFCC and the IPCC. Note the cryospheric components marked in bold and italic type. Source: GCOS (2010).

Within GCOS and GTOS, the *Terrestrial Observation Panel for Climate* (TOPC) was created in 1995 to design a global multi-level observing strategy and to set in place a *Global Terrestrial Network* (GT-Net) for all ECVs in the terrestrial domain in support of the UNFCCC. The GT-Net is envisaged as a master system of networks that provides an umbrella for existing and operational monitoring services integrating remote sensing and ground observations (GTOS 1997; 2010). It aims at facilitating the exchange of information and addresses related issues such as data access and availability, as well as the standardization of and guidelines for measurement methods. Pilot GT-Nets were established for glacier and permafrost in 1998 and 1999, respectively. An overview of the state of implementation of the GT-Net for the terrestrial ECVs is given in Table 2.2. The table clearly demonstrates that the majority of the terrestrial ECVs lack an operational GT-Net. Corresponding status reports are, hence, based on scientific results as well as on national and non-governmental monitoring activities. It is to be noted that for the cryospheric components, basic international structures do exist, and the *Global Terrestrial Network for Glaciers* (GTN-G) is probably the most sophisticated monitoring program within the terrestrial domain (GCOS, 2010). However, the implementation plan for GCOS in support of the UNFCCC (GCOS, 2010) urges full implementation of all recommended actions in order to substantially improve the availability of observational information of the ECVs. The corresponding annual costs for this implementation plan are estimated at US$ 2.5 billion in addition to the costs for maintaining and operating existing networks, systems and activities.

ECV	GT-Net	Responsible Body	Status reports
River discharge	GTN-R	Global Runoff Data Center (GRDC)	GCOS (2010), GTOS (2009a)
Water use	not yet implemented	Partly covered by GTN-Hydrology	GCOS (2010)
Ground water	not yet implemented	Partly covered by GTN-Hydrology	GCOS (2010)
Lakes	not yet implemented	Partly covered by GTN-Hydrology	GCOS (2010), GTOS (2009b)
Snow cover	not yet implemented	Partly covered by GTN-Hydrology and WMO Global Telecommunication System (WMO-GTS)	GCOS (2010), GTOS (2009c)
Glaciers and ice caps	GTN-G	World Glacier Monitoring Service (WGMS), U.S. National Snow and Ice Data Center (NSIDC), Global Land Ice Measurements from Space initiative (GLIMS)	GCOS (2010), GTOS (2009d)
Ice sheets	not yet implemented	Partly covered by space agencies	GCOS (2010)
Permafrost and seasonally frozen ground	GTN-P	International Permafrost Association (IPA), Geological Survey of Canada	GCOS (2010), GTOS (2009e)
Albedo	not yet implemented	Partly covered by World Radiation Monitoring Center with Baseline Surface Radiation Network (WRMC-BSRN)	GCOS (2010), GTOS (2009f)
Land cover	not yet implemented	Partly covered by Global Observations of Forest Cover and Land Dynamics Panel (GOFC-GOLD) and several space agencies	GCOS (2010), GTOS (2009g)
Fraction of absorbed photosynthetically active radiation (FAPAR)	not yet implemented	Partly covered by space agencies.	GCOS (2010), GTOS (2009h)
Leaf area index (LAI)	not yet implemented	Partly covered by space agencies	GCOS (2010), GTOS (2009i)
Above-ground biomass	not yet implemented	Partly covered by Global Observations of Forest Cover and Land Dynamics Panel (GOFC-GOLD) and Carbon Flux Networks (FluxNet)	GCOS (2010), GTOS (2009j)
Soil carbon	not yet implemented	-	GCOS (2010)
Fire disturbance	not yet implemented	Partly covered by Global Fire Monitoring Center (GFMC) and space agencies	GCOS (2010), GTOS (2009k)
Soil moisture	not yet implemented	-	GCOS (2010)

Table 2.2: Matrix of *Essential Climate Variables* (ECVs) in the terrestrial domain with corresponding *Global Terrestrial Networks* (GT-Nets) and operational bodies that are responsible for its systematic observation. Sources given in table.

3 Internationally Coordinated Glacier Monitoring

3.1 Historical Background, Present Organizations and Strategy

3.1.1 Global Glacier Monitoring - a Long-term Task Integrating In-situ Observations and Remote Sensing

Summary mainly based on: **Zemp, M.**, Armstrong, R., Gärtner-Roer, I., Haeberli, W., Hoelzle, M., Kääb, A., Kargel, J.S., Singh Khalsa S.J., Paul, F. & Raup, B. (accepted). Chapter 1: **Global glacier monitoring - a long-term task integrating in-situ observations and remote sensing.** In: Kargel, J.S., Bishop, M.P., Kääb, A. & Raup, B.H. (eds.). Global Land Ice Measurements from Space. Satellite mulitspectral imaging of glaciers. Praxis-Spring.

A glacier is defined as a perennial mass of surface ice originating on land and showing evidence of flow. In general, glaciers form where snow deposited during the cold/humid season does not entirely melt during warm/dry times (Paterson, 1994). The reaction of a glacier to a climatic change involves a complex chain of processes (Meier, 1984; Nye, 1960). Changes in atmospheric conditions (solar radiation, air temperature, precipitation, wind, cloudiness, etc.) influence the mass and energy balance at the glacier surface (Kuhn, 1981; Oerlemans, 2001). Air temperature plays a predominant role in this process as it is related to the radiation balance, turbulent heat exchange and solid/liquid precipitation (Ohmura, 2001). Over time periods of years and decades, changes in mass balance cause volume and thickness changes, which in turn affect the flow of ice via internal deformation and basal sliding. This dynamic reaction leads in the end to glacier length changes, that is, the advance or retreat of glacier tongues. In short, the glacier mass balance (i.e., the 'vertical' thickness change) is a relatively direct and undelayed signal of annual atmospheric conditions, whereas the advance or retreat of glacier tongues (i.e., the 'horizontal' length change) constitutes an indirect, delayed and filtered but also enhanced and easily observed signal of climatic change (Haeberli & Hoelzle, 1995; Jóhannesson, Raymond, & Waddington, 1989; Oerlemans, 2001).

Internationally coordinated glacier observation was initiated in 1894 with the founding of the *Commission Internationale des Glacier* (CIG) at the *6th International Geological Congress* in Zurich, Switzerland. In the beginning, glacier monitoring focused mainly on glacier fluctuations, particularly with the collection and publication of front variation data and after the late 1940s of glacier mass balance results (Haeberli, 2008). Periodical publishing of compiled information on glacier fluctuations started in 1895 on behalf of the CIG, which later transformed into the *International Commission on Snow and Ice* (ICSI), and in 2007 into the *International Association of Cryospheric Sciences* (IACS; see Radok 1997; Jones 2008). Starting in 1967, the data were compiled and published by the *Permanent Service on the Fluctuations of Glaciers* (PSFG; Kasser 1970; Radok 1997). The need for a worldwide inventory of existing perennial ice and snow masses was first considered during the *International Hydrological Decade* (IHD; 1965−74). As a result, a *Temporal Technical Secretariat for the World Glacier Inventory* (TTS/WGI) was established in 1975 (Radok, 1997; WGMS, 1989) with the aim to prepare guidelines for the compilation of such an inventory and to collect available datasets from different countries. In 1986, the *World Glacier Monitoring Service* (WGMS) started to maintain and continue the collection of standardized information about ongoing glacier changes, when the two former ICSI services PSFG and TTS/WGI were combined (Haeberli, 2008).

Today the WGMS is a service of the IACS within the *International Union of Geodesy and Geophysics* (IUGG) as well as of the ICSU's *World Data System* (WDS), and works under the auspices of UNEP, UNESCO, and WMO. The WGMS maintains a scientific collaboration network of principal investigators and national correspondents in all the countries involved in glacier monitoring. In close collaboration with the *US National Snow and Ice Data Center in Boulder* (NSIDC) and the *Global Land Ice Measurements from Space* (GLIMS) initiative, the WGMS has been in charge of the GTN-G since its creation in 1998 (Haeberli, Cihlar, & Barry, 2000). A schematic overview of the various parties and their link with the GTN-G is shown in Figure 3.1.

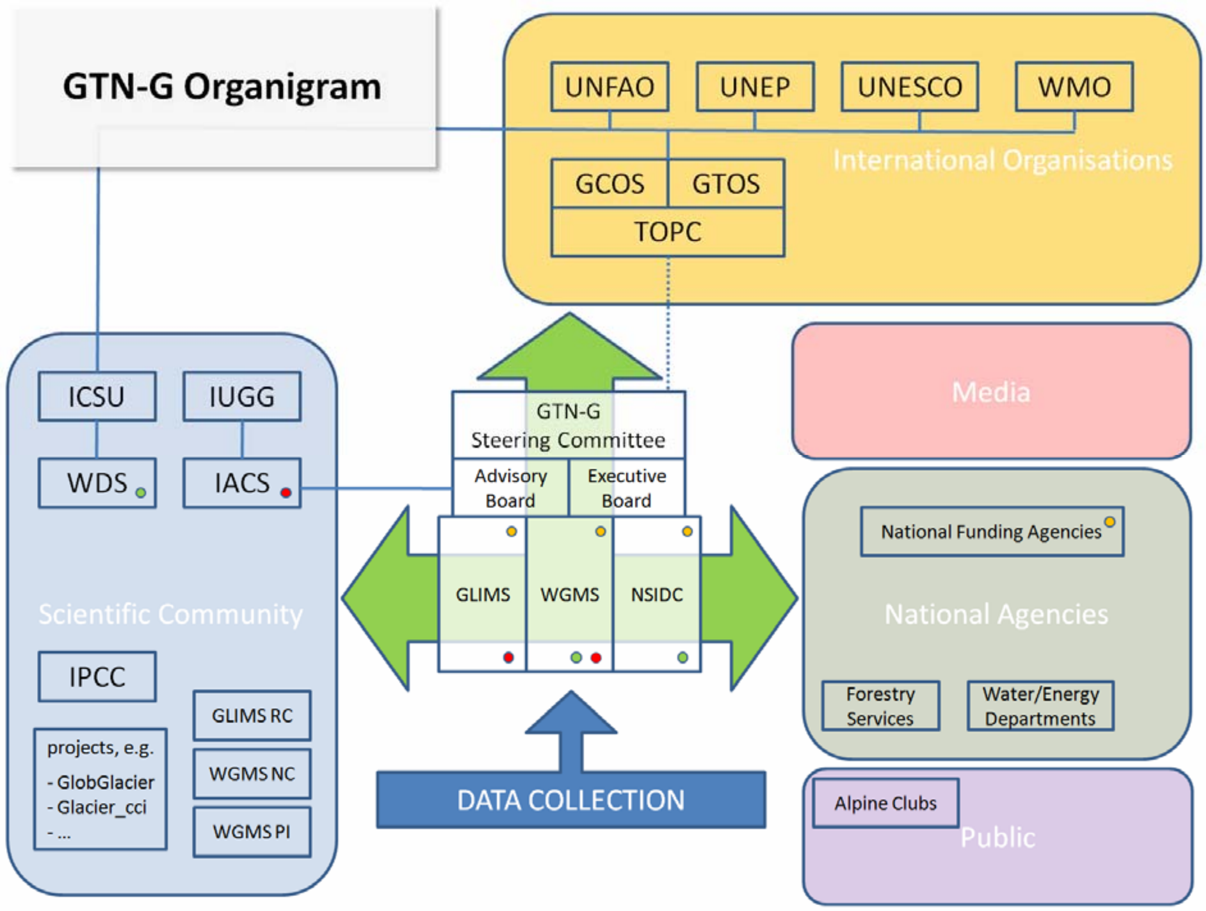

Figure 3.1: Schematic overview of the *Global Terrestrial Network for Glaciers* (GTN-G) and its interactions with international organizations, scientific community, national agencies, the media, and the general public. The figure shows the flow data compilation and dissemination (blue and green arrows, respectively) as well as the main sources of funding (orange dots) and the formal links to international bodies (red and green dots). For explanations of acronyms see text and list of abbreviations.

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 1998; 2004). As part of this strategy, the GTN-G is designed to provide quantitative, comprehensive and easily understandable 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 policymakers, 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 geo-informatics.

Numerous in-situ observation series of glacier front variations together with the positions of the moraines give a rather good qualitative overview of the global and regional glacier changes since their *Little Ice Age* (LIA) maximum extents, while mass balance measurements enable ice loss since the late 1940s to be quantified. However, the relatively few glacier mass balance series cannot truly represent the changes in global ice cover. Many regions with large amounts of ice cover are strongly underrepresented in the dataset or even completely lack observations. As a consequence, the field measurements with a high temporal resolution (but limited in spatial coverage) must be complemented by remotely sensed decadal area and volume change assessment (e.g., Rignot, Rivera, and Casassa 2003; Larsen et al. 2007; Paul and Haeberli 2008) in order to provide a representative view of the climate change impacts. In addition, numerical modeling studies are encouraged as a way to bridge the gap between local process studies and coverage at the global scale (e.g. Raper and Braithwaite 2006), to link the glacier fluctuations to the climate forcing (e.g. Greuell and Oerlemans 1986), and to downscale global and regional climate model scenarios for use in local process models (e.g., Machguth et al. 2009; Hofer et al. 2010).

3.1.2 Generic Structure and Terms of Reference of the Global Terrestrial Network for Glaciers

After its creation in 1998, the GTN-G has been run by the WGMS in rather informal cooperation with NSIDC and GLIMS (Haeberli personal comm.; Barry 1998). Among the three bodies, key expertise for in-situ measurements is generally in the domain of the WGMS, while GLIMS and NSIDC have focused mainly on remote sensing and data management of glaciers, respectively. In 2008, a *Memorandum of Understanding* was drawn up between the WGMS and NSDIC regarding the cooperation in the exchange and distribution of glacier data and standards, and interoperability between the two data archives (Haeberli & Barry, 2008). One of the specific tasks was to establish a common GTN-G *Steering Committee* to support and advise the two organizations in scientific questions of principle concerning the monitoring of glaciers and ice caps. In the same year, the WGMS submitted an official proposal for the establishment of a Steering Committee for the GTN-G and included supporting letters on behalf of NSIDC and GLIMS to the IACS *Bureau* (Zemp & Haeberli, 2008). The GTN-G *Steering Committee* was approved by the IACS *Bureau* in 2009 and at the beginning of 2001 its *Advisory Board* was then staffed with representatives from data-user and producer communities, as well as from international organizations. The following is an excerpt from the approved proposal:

1. Aim of the GTN-G Steering Committee
A GTN-G *Steering Committee* is established to coordinate, support, and advise the WGMS, the NSIDC, and the GLIMS initiative regarding the monitoring of glaciers and ice caps. The GTN-G *Steering Committee* consists of:

(a) an *Executive Board* that is responsible for (i) the development and implementation of the international observation strategy for glaciers and ice caps, (ii) providing standards for the monitoring of glacier fluctuations (e.g., length change, mass balance) and for inventories, and (iii) the compilation and distribution of such information in a standardized form, and

(b) an *Advisory Board* that is to (i) support, (ii) consult, and (iii) periodically evaluate the work of the Executive Board and its three operational bodies concerning the monitoring of glaciers and ice caps.

2. Generic Structure of the GTN-G Steering Committee

GTN-G *Executive Board*

- 1 Representative of the WGMS
- 1 Representative of the NSIDC
- 1 Representative of the GLIMS coordinating institutions

GTN-G Advisory Board

- *Division Head for Glaciers and Ice Sheets* of the IACS
- 1 Representatives of data producers (field observations)
- 1 Representatives of data producers (remote sensing)
- 1-2 Representatives of data users (glaciological community)
- 1 Representative of an international umbrella organization (e.g., *WCRP's Climate and Cryosphere project* (CliC), GCOS, GTOS, ICSU, UNEP, UNESCO, WMO)

3. Terms of Reference

- The GTN-G *Steering Committee* aims to coordinate, support and advise the WGMS, the NSIDC and the GLIMS initiative concerning the monitoring of glaciers and ice caps. It frames and adapts the monitoring strategies and standards for glacier and ice cap monitoring in the context of existing and new developments in nature, science and technology.

- • The GTN-G *Executive Board* meets approximately once a year to:
    - assess the state of the international monitoring of glaciers and ice caps,
    - coordinate the cooperation between the WGMS, the NSIDC and the GLIMS initiative,
    - establish the issues and agenda about which the *Advisory Board* shall be consulted,
    - and it reports annually on GTN-G activities to the GTN-G *Advisory Board*, to the funding agencies and umbrella organizations of the WGMS, the NSIDC, and the GLIMS initiative.

- The GTN-G Advisory Board:
    - is chaired by the *Division Head for Glaciers and Ice Sheets* of the IACS,
    - consists of the chair and a maximum of six representatives as described in the generic structure above,
    - advises the WGMS, the NSIDC and the GLIMS initiative concerning present practice and future developments in the monitoring of glaciers and ice caps, and also on the delivery of datasets to the wider glaciological community,
    - and periodically (at approximately eight-year intervals) evaluates the work of the GTN-G *Executive Board* and its three operational bodies regarding the monitoring of glaciers and ice caps by a process that consists of a self-evaluation report by the GTN-G *Executive Board*, a site visit at one of the body's location, and a final evaluation report from the GTN-G *Advisory Board*.

- The members of the GTN-G *Advisory Board* are jointly nominated by the IACS *Bureau* and the GTN-G *Executive Board*, will serve for four year renewable terms, and will normally communicate electronically.

- The GTN-G *Steering Committee* members communicate electronically on a regular basis; meetings of the full GTN-G *Steering Committee* may be called if:
  (a) requested by the *Executive Board*, or
  (b) requested by a majority of *Advisory Board* members.

3.2 Compilation, Management and Dissemination of Standardized Glacier Data

3.2.1 Overview of Available Datasets and General Data Policy

More than a century of internationally coordinated glacier monitoring has resulted in an unprecedented dataset of information about spatial glacier distribution and changes over time. These datasets include about 36,000 annual front variation observations dating back to the late 19th century, more than 3,500 annual mass balance measurements covering the past six decades as well as two types of glacier inventories: (i) the WGI (WGMS, 1989) which is based mainly on aerial photographs and maps and gives access to available detailed information on location, classification, area, length, orientation and altitude range for over 100 000 glaciers worldwide with a total area of 240,000 km^2 and preliminary estimates of the remaining glacierized regions derived from early satellite imagery; and (ii) the GLIMS database which was initiated in 1999 to continue the inventory task with space-borne sensors (cf. Bishop et al. 2004; Kargel et al. 2005). This database now contains digital outline information on over 93,000 glaciers covering more than 260,000 km^2 (status December 2010) and will grow further through input expected soon from projects dedicated to space-borne glacier monitoring such as *GlobGlacier* (www.globglacier.ch), funded by the *European Space Agency* (ESA), and its successor the *Glacier_cci* (www.esa-cci.org), or the *European Union* science program *Ice2Sea* (www.ice2sea.eu). Additional datasets which are compiled and disseminated within GTN-G are glacier thickness and volume changes, reconstructed glacier front variations, as well as collections of glacier-related special events (e.g., glacier surges, calving, avalanches, lake outburst floods), glacier photographs, and printed glacier maps. In 1989, an initial attempt was made to set up a glacier database with the collected and published data in the WGI and in the *Fluctuations of Glaciers* series as well as those compiled from the literature (Hoelzle, Haeberli, Dischl, & Peschke, 2003; Hoelzle & Trindler, 1998). Nowadays, all datasets are stored in relational databases (see Figure 3.2) hosted at WGMS in Zurich and/or at NSIDC in Boulder and made readily available to the scientific community, non- and governmental agencies, the media, and the wider public. Since 2010, a web-based meta-data portal provides an overview of available glacier data and information (Zemp, Hoelzle, & Haeberli, 2009) and corresponding files are available for client-side data exploration in virtual globes (cf. Ballagh et al. 2010).

Figure 3.2: Schematic overview of the four glacier databases within the *Global Terrestrial Network for Glaciers* (GTN-G) storing *Fluctuations of Glaciers* (FoG), the *World Glacier Inventory* (WGI), the *Global Land Ice Measurements from Space* inventory (GLIMS), and the *Glacier Photograph Collection* (GPC). For all relational databases, the principal relations (upper-case letters) are shown with the attributes (lower-case letters) forming corresponding primary keys (#) and defining the glacier location.

A basic requirement for advancing research is free and unrestricted international sharing of high-quality, long-term, and standardized data and information products. It is in this spirit that ICSU endorses as a general policy the fundamental principle of full and open exchange of data and information for scientific and educational purposes (ICSU, 2004). Within the GTN-G, a one-year retention period is granted to allow investigators time to properly analyze, document, and publish their data before submitting them in standardized format to GTN-G operational bodies such as WGMS, NSIDC; and GLIMS. All data submitted to the GTN-G are considered public domain for non-commercial use and are made digitally available through the operational services at no cost. It is pointed out that all data may be subject to errors and inaccuracies. It is, therefore, strongly recommended to perform data quality checks before any analysis and interpretation of the data. The use of data and information from the GTN-G requires acknowledgement to the GTN-G operational body (i.e., WGMS, NSIDC, and GLIMS) and/or the original investigators and sponsoring agencies according to the available meta-information.

3.2.2 Overview of Published Data Reports

Since the very beginning of internationally coordinated glacier monitoring, the collected data has been published in written reports starting with the *Discours préliminaire sur les variations périodiques des glaciers* and *Rapport sur les variations périodiques des glaciers* by Forel in 1895 and Forel and Du Pasquier in 1896, respectively. The first reports were published on behalf of the CIG in French, Italian, German, and English; since 1967, all publications have appeared in English (Haeberli, 1998). The first reports contain mainly qualitative observations, with the exception of the glaciers in the Alps and Scandinavia, which have been well documented by quantitative measurements right from the start.

Data reports published on behalf of the *Commission Internationale des Glacier* (CIG):

Forel, F.A. (1895). **Les variations périodiques des glaciers. Discours préliminaire.** Extrait des Archives des Sciences physiques et naturelles XXXIV, 209-229.

Forel, F.A. & Du Pasquier, L. (1896). **Les variations périodiques des glaciers. Ier Rapport, 1895**. Extrait des Archives des Sciences physiques et naturelles 101/4 (2), 129-147.

Forel, F.A. & Du Pasquier, L. (1897). **Les variations périodiques des glaciers. IIme Rapport, 1896**. Extrait des Archives des Sciences physiques et naturelles 102/4 (4), 218-245.

Richter, E. (1898). **Les variations périodiques des glaciers. IIIme Rapport, 1897.** Extrait des Archives des Sciences physiques et naturelles 103/4 (6), Genève, 22-55.

Richter, E. (1899). **Les variations périodiques des glaciers. IVme Rapport, 1898.** Extrait des Archives des Sciences physiques et naturelles 104/4 (8), Genève, 31-61.

Richter, E. (1900). **Les variations périodiques des glaciers. Vme Rapport, 1899.** Extrait des Archives des Sciences physiques et naturelles 105/4 (10), Genève, 26-45.

Finsterwalder, S. & Muret, E. (1901). **Les variations périodiques des glaciers. VIme Rapport, 1900.** Extrait des Archives des Sciences physiques et naturelles 106/4 (12), 118-131.

Finsterwalder, S. & Muret, E. (1902). **Les variations périodiques des glaciers. VIIme Rapport, 1901**. Extrait des Archives des Sciences physiques et naturelles 107/4 (14), 282-302.

Finsterwalder, S. & Muret, E. (1903). **Les variations périodiques des glaciers. VIIIme Rapport, 1902**. Extrait des Archives des Sciences physiques et naturelles 108/4 (15), 661-677.

Reid, H. & Muret, E. (1904). **Les variations périodiques des glaciers. IXme Rapport, 1903.** Extrait des Archives des Sciences physiques et naturelles 109/4 (18), Genève, 160-195.

Reid, H. & Muret, E. (1905). **Les variations périodiques des glaciers. Xme Rapport, 1904.** Extrait des Archives des Sciences physiques et naturelles 110/4 (20), Genève, 62-74.

Reid, H. & Muret, E. (1906). **Les variations périodiques des glaciers. XIme Rapport, 1905.** Zeitschrift für Gletscherkunde und Glazialgeologie I, 1-21.

Brückner, E. & Muret, E. (1908). **Les variations périodiques des glaciers. XIIme Rapport, 1906.** Zeitschrift für Gletscherkunde und Glazialgeologie II, 161-198.

Brückner, E. & Muret, E. (1909). **Les variations périodiques des glaciers. XIIIme Rapport, 1907.** Zeitschrift für Gletscherkunde und Glazialgeologie III, 161-185.
Brückner, E. & Muret, E. (1910). **Les variations périodiques des glaciers. XIVme Rapport, 1908.** Zeitschrift für Gletscherkunde und Glazialgeologie IV, 161-176.
Brückner, E. & Muret, E. (1911). **Les variations périodiques des glaciers. XVme Rapport, 1909.** Zeitschrift für Gletscherkunde und Glazialgeologie V, 177-202.
Rabot, C. & Muret, E. (1911). **Les variations périodiques des glaciers. XVIme Rapport, 1910.** Zeitschrift für Gletscherkunde und Glazialgeologie VI, 81-103.
Rabot, C. & Muret, E. (1912). **Les variations périodiques des glaciers. XVIIme Rapport, 1911.** Zeitschrift für Gletscherkunde und Glazialgeologie VII, 37-47.
Rabot, C. & Mercanton, P.L. (1913). **Les variations périodiques des glaciers. XVIIIme Rapport, 1912.** Zeitschrift für Gletscherkunde und Glazialgeologie VIII, 81-103.
Rabot, C. & Muret, E. (1913). **Supplément au XVIIme rapport sur les variations périodiques des glaciers, 1911.** Zeitschrift für Gletscherkunde und Glazialgeologie VII, 191-202.

After the *First World War*, the publications appeared less frequently, under the title of *Rapport sur les variations de longueur des glaciers*, and since 1933 on behalf of ICSI. In that period, the official reports mainly focus on Europe, with additional reports from selected regions outside Europe published in the same journal issue.

Data reports published on behalf of the *Commission Internationale des Glacier* (CGI), which after 1948 became the *International Commission of Snow and Ice* (ICSI), of the *International Association of Scientific Hydrology* (IASH; later the *International Association of Hydrological Sciences*: IAHS):

Mercanton, P.L. (1930). **Rapport sur les variations de longueur des glaciers de 1913 á 1928. Chaîne des Alpes; Scandinavie.** IAHS 14, 53 pp.
Mercanton, P.L. (1934). **Rapport sur les variations de longueur des glaciers de 1928 á 1931. Chaîne des Alpes; Scandinavie.** IAHS 20, 229-250.
Matthes, F.E. (1934). **Report for 1931-1932 of the Committee on Glaciers of the American Geophysical Union.** IAHS 20, 251-264.
Mercanton, P.L. (1936). **Rapport sur les variations de longueur des glaciers de 1931 á 1935. Chaîne des Alpes; Scandinavie et Islande.** IAHS 22, 430-456.
Ahlmann, H.W. (1948). **Recent glaciological investigations in Sweden.** IAHS 30, 262-263.
Anonyme (1948). **Variation des glaciers en Suède, Islande et Norvège.** IAHS 30, 257-261.
Field, W.O. (1948). **The variations of Alaskan glaciers (1935-1947).** IAHS 30, 277-282.
Meek, V. (1948). **Glacier observations in the Canadian Cordillera.** IAHS 30, 264-275.
Mercanton, P.L. (1948). **Rapport sur les variations de longueur des glaciers de 1935 á 1946. Alpes francaises, suisses, italiennes et autrichiennes. Variations des glaciers en Suède, Islande et Norvège.** IAHS 30, 233-256.
Odell, N.E. (1948). **Glacial features of the Lloyd George Mountains (British Columbia).** IAHS 30, 276.
Oppenheim (1948). **Deglaciation in Columbia.** IAHS 30, 285-287.
Spann, H.J. (1948). **Report on glacier recession in Peru.** IAHS 30, 283-284.
Field, W.O. (1952). **Report on the Northern American glaciers.** IAHS 32, 120-128.
Mercanton, P.L. (1952). **Rapport sur les variations de longueur des glaciers européens, de 1947 á 1950.** IAHS 32, 107-119.
Harrison, A.E. (1954). **Fluctuations of the Nisqually Glacier, Mt Rainer, Washington, during the last two centuries.** IAHS 39, 506-510.
Heusser, C.J. (1954). **Glacier fluctuations in the Canadian Rockies.** IAHS 39, 493-497.
Johnson, A. (1954). **Observations on the Nisqually and other glaciers in the Northwestern United States.** IAHS 39, 511-516.
Mercanton, P.L. (1954). **Rapport sur les variations de longueur des glaciers européens, en 1950-51, 1951-52, 1952-53.** IAHS 32, 478-490.
Mercanton, P.L. (1958). **Rapport sur les variations de longueur des glaciers européens, en 1953/54, 1954/55, 1955/56.** IAHS 46, 358-371.

Mercanton, P.L. (1961). **Rapport sur les variations de longueur des glaciers européens, en 1956/57, 1957/58, 1958/59.** IAHS 54, 366-378.

Starting in 1967, the once again worldwide data compilations have been published in five-yearly intervals under the *Fluctuations of Glaciers* series, first by the PSFG and, after 1986, by the WGMS. In 1945, continuous (seasonal) mass balance measurements based on the direct glaciological method (cf. Østrem and Brugman 1991) were initiated on Storglaciären, Sweden (Holmlund, Jansson, & Pettersson, 2005). This new type of data has been included, together with detailed meta-data in tabular form, in the *Fluctuations of Glaciers* series since the very first volume.

Data reports published by the *Permanent Service for the Fluctuations of Glaciers* (PSFG):

PSFG (1967). **Fluctuations of Glaciers 1959-1965 (Vol. I).** P. Kasser (ed.), IAHS (ICSI) / UNESCO, Permanent Service on Fluctuations on Glaciers, Zurich, Switzerland: 52 pp.

PSFG (1973). **Fluctuations of Glaciers 1965-1970 (Vol. II).** P. Kasser (ed.), IAHS (ICSI) / UNESCO, Permanent Service on Fluctuations on Glaciers, Zurich, Switzerland: 357 pp.

PSFG (1977). **Fluctuations of Glaciers 1970-1975 (Vol. III).** F. Müller (ed.), IAHS (ICSI) / UNESCO, Permanent Service on Fluctuations on Glaciers, Zurich, Switzerland: 269 pp.

PSFG (1985). **Fluctuations of Glaciers 1975-1980 (Vol. IV).** W. Haeberli (ed.), IAHS (ICSI) / UNESCO, Permanent Service on Fluctuations on Glaciers, Zurich, Switzerland: 265 pp.

As a consequence of the rising interest in, and in order to accelerate the access to, the glacier mass balance information, preliminary values on the specific annual mass balance as well as on the equilibrium line altitude and the accumulation area ratio have been published by the WGMS in the bi-annual *Glacier Mass Balance Bulletin* series. Based on an agreement with the TOPC of GCOS/GTOS, preliminary glacier mass balance results have been made available annually on the WGMS website since 1999, as of one year after the end of the measurement period. In contrast to the periodical publications on glacier fluctuations there is just one status report on the WGI which was published in 1989 (WGMS, 1989). Over the past years, the GLIMS community has been drafting – but not yet brought to publication – a GLIMS book and has been discussing the regular issuing of a GLIMS bulletin. In 2008, the WGMS published an overview of all available datasets on glacier distribution and fluctuations in a UNEP report (WGMS, 2008a).

Data reports published by the *World Glacier Monitoring Service* (WGMS):

WGMS (1988). **Fluctuations of Glaciers 1980-1985 (Vol. V).** Haeberli, W. & Müller, P. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 290 pp.

WGMS (1989). **World glacier inventory - Status 1988.** Haeberli, W., Bösch, H., Scherler, K., Østrem, G. & Wallén, C. C. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 458 pp.

WGMS (1991). **Glacier Mass Balance Bulletin No. 1 (1988-1989).** Haeberli, W. & Herren, E. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 70 pp.

WGMS (1993a). **Glacier Mass Balance Bulletin No. 2 (1990-1991).** Haeberli, W., Herren, E. & Hoelzle, M. (eds.),. IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 74 pp.

WGMS (1993b). **Fluctuations of Glaciers 1985-1990 (Vol. VI).** Haeberli, W. & Hoelzle, M. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 322 pp.

WGMS (1994). **Glacier Mass Balance Bulletin No. 3 (1992-1993).** Haeberli, W., Hoelzle, M. & Bösch, H. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 80 pp.

WGMS (1996). **Glacier Mass Balance Bulletin No. 4 (1994-1995).** Haeberli, W., Hoelzle, M. & Suter, S. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 90 pp.

WGMS (1998). **Fluctuations of Glaciers 1990-1995 (Vol. VII).** Haeberli, W. , Hoelzle, M., Suter, S. & Frauenfelder, R. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 296 pp.

WGMS (1999). **Glacier Mass Balance Bulletin No. 5 (1996-1997).** Haeberli, W., Hoelzle, M. & Frauenfelder, R. (eds.),. IAHS (ICSI) / UNEP / UNESCO. World Glacier Monitoring Service, Zurich, Switzerland: 96 pp.

WGMS (2001). **Glacier Mass Balance Bulletin No. 6 (1998-1999).** Haeberli, W., Frauenfelder, R. & Hoelzle, M. (eds.),. IAHS (ICSI) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 93 pp.

WGMS (2003). **Glacier Mass Balance Bulletin No. 7 (2000-2001).** Haeberli, W., Frauenfelder, R., Hoelzle, M. & Zemp, M. (eds.), IAHS (ICSI) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 87 pp.

WGMS (2005a). **Glacier Mass Balance Bulletin No. 8 (2002-2003).** Haeberli, W., Noetzli, J., Zemp, M., Baumann, S., Frauenfelder, R. & Hoelzle, M. (eds.), IUGG (CCS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 100 pp.

WGMS (2005b). **Fluctuations of Glaciers 1995-2000 (Vol. VIII).** Haeberli, W., Zemp, M., Frauenfelder, R., Hoelzle, M. & Kääb, A. (eds.), IUGG (CCS) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 288 pp.

WGMS (2007). **Glacier Mass Balance Bulletin No. 9 (2004-2005).** Haeberli, W., Zemp, M. & Hoelzle, M. (eds.), ICSU (FAGS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 100 pp.

WGMS (2008a). **Global Glacier Changes: facts and figures.** Zemp, M., Roer, I., Kääb, A., Hoelzle, M., Paul, F. & Haeberli, W. (eds.), UNEP, World Glacier Monitoring Service, Zurich, Switzerland: 88 pp.

WGMS (2008b). **Fluctuations of Glaciers 2000-2005 (Vol. IX).** Haeberli, W., Zemp, M., Kääb, A., Paul, F. & Hoelzle, M. (eds.), ICSU (FAGS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 266 pp.

WGMS (2009). **Glacier Mass Balance Bulletin No. 10 (2006–2007).** Haeberli, W., Gärtner-Roer, I., Hoelzle, M., Paul, F. & Zemp, M. (eds.), ICSU (WDS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 96 pp.

With the availability of glacier data in digital formats, the need for printing glacier data reports has been discussed repeatedly. Both the last evaluation of the WGMS through IACS in 2006 and the last WGMS *General Assembly of National Correspondents* in 2010 clearly endorsed the concept of printing and worldwide shipment of reports (IACS, 2006; WGMS, 2010). Corresponding key arguments are (i) periodic publications as a driving process of an active data compilation, (ii) data safety through worldwide distribution printed reports, and (iii) production and distribution of large color maps.

3.2.3 Fluctuations of Glaciers 2000−2005 (Vol. IX)

Summary mainly based on: WGMS (2008b). **Fluctuations of Glaciers 2000-2005** (Vol. IX). Haeberli, W., **Zemp, M.**, Kääb, A., Paul, F. & Hoelzle, M. (eds.), ICSU (FAGS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 266 pp.

Volume IX of the *Fluctuations of Glaciers* (WGMS, 2008b) focuses primarily on the time period from 2000 to 2005. It is the most recent addition to the continuing series of publications containing internationally collected and standardized data on current changes in glaciers throughout the world. It was prepared by the WGMS under the auspices of ICSU’s *Federation of Astronomical and Geophysical Data Analysis Services* (FAGS), IUGG(IACS), UNEP, UNESCO, and WMO as a contribution to the GTN-G as part of GCOS/GTOS, to the *Division of Early Warning and Assessment* and the *Global Environment Outlook* as part of UNEP, and the *International Hydrological Program* (IHP) as part of UNESCO. The objective of the publication at five-yearly intervals is to reproduce a global set of data which affords a general view of glacier changes, encourages more extensive measurements, invites further processing of results, facilitates consultation with the other data sources, and serves as a basis for research. In fact, the publication of this standardized dataset is the main driver of the active, international data collection and should be regarded as a working tool for the scientific community, especially with regard to the fields of glaciology, climatology, hydrology, and quaternary geology. In this way, the printing and shipment of the volumes to several hundred of libraries and institutions all over the world constitutes a core element in ensuring the long-term availability of the collected data and published maps.

The volume starts with two prefaces by UNEP and UNESCO, a foreword by IACS (IUGG), as well as preliminary remarks and acknowledgements by the WGMS editorial board. The volume is organized in eight chapters, a list of the literature, and the comprehensive data appendix. Chapter 1 provides an overview of the preparation of the present volume (2000−2005) from the call-for-data that was sent out to the WGMS *National Correspondents* one year after the end of the observation periods (i.e. September 2006) to the distribution of the final press proof in October 2008. All received information, from meta-data to glacier fluctuation data, was summarized country by country. Chapter 2 covers information on the data compilation, the investigators and sponsoring agencies involved, the methodologies applied, the state of national glacier monitoring, and related publications. Full address details on sponsoring agencies and sources of data for the various countries, as well as of the WGMS *National Correspondents* are given in the third chapter. Chapter 4 documents index measurements on glacier fluctuations in cases where more complex observations are not possible, especially in relation to remote glaciers and glaciers which are systematically studied using reduced stake networks in combination with statistical considerations or flow calculations. This chapter also summarizes information on special events which may pose risks to human activities, such as glacier surges, outbursts of ice-dammed lakes, ice avalanches, and drastic retreat of tidal glaciers due to calving instabilities or eruptions of ice-clad volcanoes. In Chapter 5, brief descriptions related to the ten annexed glacier maps are added. These include information regarding the purpose of the particular map, its accuracy, and details on the surveying, cartography and reproduction, as well as references to related publications. Chapters 6 and 7 provide summary information from the glacier remote sensing community on the GLIMS initiative and the *ESA* project *GlobGlacier*, respectively. General comments and perspectives for the future by the editors are found in Chapter 8, followed by the list of literature. The Appendix starts with explanatory notes on the more than 100 standardized attributes that were used in the call-for-data, followed by seven data tables with general information on the observed glaciers, variations in the position of the glacier fronts from 2000−2005 and addenda from earlier years, mass balance summary data from 2000−2005 and addenda from earlier years, mass balance versus altitude for selected glaciers, as well as changes in area, volume and thickness. In order to facilitate the location of data for any glacier within the various tables, glaciers are organized alphabetically and according to the country where they are situated. In addition, an alphabetic index of glaciers is given at the end of the volume.

Volume IX of the *Fluctuations of Glaciers* contains information on 723 glaciers from 27 countries, or regions such as Antarctica. This includes data on glacier front variations during the period 2000 to 2005 from 605 glaciers in 22 countries, with addenda from earlier years for 107 glaciers in eleven countries, mass balance results from the observation period covered for a total of 112 glaciers in 21 countries, with addenda for 28 glaciers in ten countries, detailed information on mass balance versus altitude from 58 glaciers in 16 countries, and data relating to changes in area, volume, and thickness for 41 glaciers in 11 countries. Index measurements were received from three countries as well as information on 21 special events in ten countries; ten special glacier maps from five countries are included in the back pocket of the volume.

From the more than 2100 reported front variations of the five-year observation period, 87% of them are document a glacier retreat. Mass balance results indicate a strong acceleration of glacier melting. Rates of mass losses (-0.60 m w.e.) from the 30 ‘reference’ glaciers with (almost) continuous measurements since 1976 more than doubled the mean value observed during the two preceding decades 1980–2000 (-0.29 m w.e.). The average annual mass loss of 0.58 m water equivalent (w.e.) for the decade 1996–2005 is more than twice the loss rate during the period 1986–1995 (-0.25 m w.e.), and more than four times the rate of the period 1976–1985 (-0.14 m w.e.). The mean of the 30 ‘reference’ glaciers is influenced by the great number of Alpine and Scandinavian glaciers but closely corresponds to the mean value calculated using only one single (in some places averaged) value for each of the mountain ranges concerned, and can be considered representative for all measured mass balances according to analyses using various statistic approaches (Kaser, Cogley, Dyurgerov, Meier, & Ohmura, 2006; Zemp, Hoelzle, & Haeberli, 2009). While 34% of the ‘reference’ glaciers had an overall positive balance during 1976–1995, only two (7%) of them had an overall mass gain over the past decade (1996–2005). This indicates that glacier shrinkage not only becomes faster but also more spatially uniform. Further analysis requires detailed consideration of aspects such as glacier sensitivity and feedback mechanisms. The cumulative mass balances reported for the individual glaciers reflect not only regional climatic variability, but also marked differences in the sensitivity of the observed glaciers.

Glacier fluctuation data compiled and disseminated by the WGMS is widely used in order to analyze regional and global glacier changes as well as their impact on hydrology, natural hazards and sea level changes. Moreover, each volume of the *Fluctuations of Glaciers* provides a review of ongoing glacier monitoring and research activities, scientists and institutions currently active, of the related literature, and last but not least, a ’compass’ to guide the reader through the sea of acronyms for national and international organizations involved.

3.2.4 Glacier Mass Balance Bulletin No. 10 (2006−2007)

Summary mainly based on: WGMS (2009). **Glacier Mass Balance Bulletin No. 10 (2006–2007)**. Haeberli, W., Gärtner-Roer, I., Hoelzle, M., Paul, F. and **Zemp**, M. (eds.), ICSU (WDS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 96 pp.

The *Glacier Mass Balance Bulletin No. 10* (WGMS, 2009) reports the results from the hydrological years 2005/06 and 2006/07 and is the latest issue in a long-term series of publications. As the *Fluctuations of Glaciers Vol. IX*, it was prepared by the WGMS under the auspices of ICSU(now: WDS), IUGG (IACS), UNEP, UNESCO, and WMO as a contribution to the GTN-G as part of GCOS/GTOS, to the *Division of Early Warning and Assessment* and the *Global Environment Outlook* as part of UNEP, and the IHP as part of UNESCO. The *Glacier Mass Balance Bulletin* series is designed to speed up and facilitate access to information concerning glacier mass balances by reporting measured values from selected reference glaciers at two-year intervals. The results of glacier mass balance measurements are made more easily understandable for non-specialists through the use of graphic illustrations in addition to numerical data. The bulletin complements the publication series *Fluctuations of Glaciers* (WGMS 2008b, and earlier volumes), where the full collection of digital data, including geodetic volume changes and the more numerous observations of glacier length variation, can be found. The publication of standardized glacier mass balance data in the *Glacier Mass Balance Bulletin* is restricted to measurements which are based on the direct glaciological method and requested to be compared, and if necessary, adjusted to geodetic or photogrammetric surveys repeated at about decadal time intervals. Within the integrated and multi-level monitoring strategy of GTN-G (Haeberli, 1998; 2004), glacier mass balance measurements are used at a detailed level within major climatic zones to improve process understanding and calibration of numerical models as well as with cost-saving methodologies to determine regional glacier volume change within major mountain systems.

The bulletin is organized in five chapters starting with an introduction and general information on the glaciers with available measurements in the observation period covered and those with (interrupted) long-term data series, and includes a corresponding global overview map. In Chapter 2, basic information is given on the mass balance results of the two observation years together with graphs of cumulative mass balance series, organized country by country. Chapter 3 provides detailed information with text, photograph, maps, and key graphs of selected glaciers with long-term data series and/or located in strategically important regions. Conclusion, global statistics, and acknowledgements are found in Chapter 4, followed by full address details of *Principal Investigators* and *National Correspondents* in Chapter 5.

The latest issue includes basic information on specific mass balance, accumulation area ratio, and equilibrium line altitude of the observation periods 2005/06 and 2006/07 for 111 glaciers in 24 countries, or regions such as Greenland and Antarctica, and detailed information for 16 glaciers. Taking the two reported years together, the mean mass balance of the 30 glaciers with continuous observation series, back to 1980 or earlier, was -962 mm w.e. per year. This represents more than one meter of ice thickness loss per year and exceeds by about 35 % the mean mass balance since the turn of the century (2000–2007: -706 mm w.e.), and is more than three times the average between 1980 and 1999 (-296 mm w.e.). During this most recent time interval, the maximum loss in the 1980–1999 time period (-728 mm w.e. in 1998) was already exceeded for the third time (-1269 mm w.e. in 2003, -744 mm w.e. in 2004, -1247 mm in 2006); the percentage of positive glacier mass balances decreased from an average of 32 % in the 1980s to 18 % and there were no more years with an overall positive mass balance (15 % during 1980–1999). The melt rate and loss in glacier thickness continues to be extraordinary. This development further confirms the accelerating trend in worldwide glacier disappearance, which has become more and more obvious during the past two decades. The mean of the 30 glaciers included in the analysis is influenced by the large proportion of Alpine and Scandinavian glaciers. For this reason, a mean value is also calculated using only one single value (averaged) for each of the 9 mountain ranges concerned. Furthermore, a mean was calculated for all mass balances available, independently of record length. In their general trend and magnitude, all three averages rather closely relate to each other and are in good agreement with the results from a moving-sample-averaging of all available data (cf. Kaser et al. 2006; Zemp, Hoelzle, and Haeberli 2009).

From the measured mass losses and thickness reductions, it is evident that several network glaciers with important long-term observations may not survive for many more decades. A special challenge therefore consists in developing a strategy for ensuring the continuity of adequate mass balance observations under such extreme conditions (Zemp, Hoelzle, & Haeberli, 2009).

3.3 Implementation and Upgrading of Guidelines and Standards

Internationally coordinated glacier monitoring requires common guidelines and standards with respect to methodology, terminology, and (meta-) data exchange formats. This is widely accepted and easily claimed (e.g., ICSU 2004; GCOS 2010; GTOS 2010) but its implementation – especially within a scientific collaboration network – is rather challenging. The main reasons, among others, are the limited capacity and lack of authoritative power of the international organizations involved, as well as the non-monetary and scientific nature of environmental monitoring. As a consequence, guidelines and standards evolve within the community and are dependent on the dedication of leading institutions and individuals. Long-standing monitoring services, such as the WGMS and its predecessor organizations – making active calls for standardized data – together with the involvement of leading scientists, can influence this to a certain degree. Recently, the GTOS secretariat at FAO proposed a work plan for developing observational standards and protocols for the terrestrial ECVs that conform to the *International Organization for Standardization* (cf. GTOS 2010). The feasibility, implications, and final benefit of such a costly and administratively complex approach for a scientific collaboration network are, however, controversial.

The next section (3.3.1) provides an overview of existing guidelines and standards that have become widely accepted (and cited) within the GTN-G and the glacier research community. In addition, brief notes are given on new developments and shifting paradigms. The subsequent sections (3.3.2−3.3.4) detail current efforts extending and complementing the existing guidelines and standards.

3.3.1 Overview of Existing Guidelines and Standards

The concepts in place at the onset of internationally coordinated glacier monitoring focused on the standardized compilation of front variations in order to detect periodicities of glacier variations indicating an external/global forcing (Forel, 1895). In the second half of the 20th century, the monitoring strategy became more integrative, with new observation types evolving such as geodetic volume changes or glacier mass balances. The integration of glacier monitoring into the climate-related observing system (Haeberli, Cihlar, & Barry, 2000) finally led to an integrative and tiered strategy with the objective of combining in-situ observations with remote sensing and modeling (Haeberli 1998; 2004). Recent updates include a review of available guidelines and standards (GTOS, 2009d) and more detailed specification for sensors suitable for the monitoring of glaciers and ice caps from space (GCOS 2006; 2010; IGOS 2007). Within this general development, several shifts in paradigm have taken place, such as the changes in monitoring focus from front variation to mass balance observations at individual glaciers, and recently to integrative change assessments over entire mountain ranges. Also, the original concept to assess the spatio-temporal representativeness of the few long-term mass balance observations with the larger number of front variation series (Haeberli 1998; 2004) has evolved (Haeberli, Hoelzle, Paul, & Zemp, 2007). Today, the primary use of front variation observations is (still) considered as the key to the past, but the spatial representativeness of the mass balance measurements for its mountain ranges is more commonly assessed based on the results from differencing digital elevation models from various points in time (and various sources; cf. Paul and Haeberli 2008; Berthier et al. 2010). Another notable change in focus is the use of glacier mass balance for hydrological purposes versus its qualification for the quantification of the related (climate) forcing (cf. Elsberg et al. 2001; Harrison et al. 2005).

Guidelines and standards relating to the international glacier monitoring strategy:

- Haeberli, W. (1998). **Historical evolution and operational aspects of worldwide glacier monitoring.** In: Haeberli, W., Hoelzle, M. & Suter, S. (eds.). Into the Second Century of World Glacier Monitoring - Prospects and Strategies, UNESCO publishing, Paris, 35-51.
- Haeberli, W., Cihlar, J. & Barry, R.G. (2000). **Glacier monitoring within the Global Climate Observing System.** Annals of Glaciology, 31, 241-246.
- Haeberli, W. (2004). **Glaciers and ice caps: historical background and strategies of world-wide monitoring.** In: Bamber, J.L. & Payne, A.J. (eds.): Mass balance of the cryosphere. Cambridge University Press, Cambridge, 559-578.
- Haeberli, W., Hoelzle, M., Paul, F. & Zemp, M. (2007). **Integrated monitoring of mountain glaciers as key indicators of global climate change: the European Alps.** Annals of Glaciology 46, 150-160.
- GCOS (2006, 2010). **Systematic observation requirements for satellite-based products for climate.** Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC", Report GCOS-107 (WMO/TD No. 1338), 90 pp. Updated in 2010 (GCOS-138).
- GTOS (2009). **Assessment oft the status of the development of the standards for the terrestrial Essential Climate Variables: T06 - Glaciers and Ice Caps.** Zemp, M., Gärtner-Roer, I., Haeberli, W., Hoelzle, M., Paul, F., Armstrong, R., Barry, R., Cihlar, J., Kääb, A., Kargel, J., Khalsa, S.J., Monteduro, M., Raup, B., Seiz, G. & Sessa, R. (eds.), Global Terrestrial Observing System, 61, 17 pp.
- IGOS (2007). **IGOS Cryosphere Theme for the monitoring of our environment from space and from earth**, 122 pp.

Guidelines and standards for glacier fluctuations are available for direct measurements of front variations by Forel (1895) which were updated and more detailed by Kasser in PSFG (1967) and of mass balances by Østrem and Brugman (1991), which evolved from Østrem and Stanley (1966; 1969), and by Kaser, Fountain, and Jansson (2003). A first consensus on a common terminology related to mass balance measurements was published in Anonymous (1969) and UNESCO/IASH (1970; 1973). Based broadly on these references, the WGMS has set up its guidelines for data submission (WGMS 2007, and earlier versions) with periodical updates related to the revision of the database structure. Recent development aim at the homogenization (e.g. Huss, Bauder, and Funk 2009; Fischer 2010; Koblet et al. 2010) as well as of the validation and calibration of long-term observation series (e.g., Thibert et al. 2008; Huss, Bauder, and Funk 2009; Zemp et al. 2010) in order to provide uncertainty estimates with the measurement results. It is notable that there is a general lack of guidelines and standards for the operational remotely-sensed monitoring of glacier fluctuations. An overview of basic sensors and techniques as well as related references to scientific publications can, however, be found in Kääb (2005) and on the website of the *GlobGlacier* project (www.globglacier.ch), funded by the ESA.

Guidelines and standards relating to measurements of glacier fluctuations:

- Anonymous (1969). **Mass-balance terms**. Journal of Glaciology, 8(52), 3–7.
- 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., & 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 program. IHP-VI, Technical Documents in Hydrology, No. 59, UNESCO, Paris. 107 pp. + Appendices.
- Østrem, G. & 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. & Brugman, M. (1991), **Glacier mass-balance measurements: a manual for field and office work**. NHRI Science Report.

- PSFG (1967). **Fluctuations of Glaciers 1959–1965 (Vol. I)**. P. Kasser (ed.), IAHS (ICSI) / UNESCO, Permanent Service on Fluctuations on Glaciers, Zurich, Switzerland, 52 pp.
- 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 (2009, and earlier versions). **Submission of glacier fluctuation data to the World Glacier Monitoring Service - general guidelines and attribute descriptions.** WGMS, Zurich, Switzerland, 16 pp.

The establishment of the TTS/WGI following the IHD (1965–74) resulted in several publications related to the compilation of a snapshot of the distribution of the world's glaciers, mainly based on aerial photography and maps (UNESCO 1970; Müller, Caflisch, and Müller 1977; Müller 1978; Scherler 1983). The common underlying concepts of these instructions are the manual delineation of the glaciers and the storage of the derived information in tabular forms related to a glacier point coordinate.

Guidelines and standards related to the World Glacier Inventory (mainly based on aerial photography and maps):

- Müller, F., Caflisch, T. & Müller, G. (1977, eds.). **Instructions for the compilation and assemblage of data for a world glacier inventory.** IAHS(ICSI)/UNESCO report, Temporal Technical Secretariat for the World Glacier Inventory (TTS/WGI), ETH Zurich, Switzerland.
- Müller, F. (1978, ed.). **Instructions for the compilation and assemblage of data for a world glacier inventory; Supplement: Identification/glacier number.** IAHS(ICSI)/UNEP/UNESCO report, Temporal Technical Secretariat for the World Glacier Inventory (TTS/WGI), ETH Zurich, Switzerland.
- Scherler, K. (1983, ed.). **Guidelines for preliminary glacier inventories.** IAHS(ICSI)/ 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 GLIMS initiative can be seen as the continuation of the global glacier mapping tasks started with the WGI based on satellite data. The guidelines and standards developed by the GLIMS community (see below) are developed for optical sensors (e.g., LandSat TM/ETM+, SPOT HRV, Terra ASTER) and for the manual or (semi-) automatic (cf. Paul et al. 2002; Paul 2007) determination of glacier outlines. These digital outlines facilitate change assessments as soon as repeat inventories are available. Elevation-related parameters are usually derived from digital elevation models that are available at national or global (e.g., Terra ASTER, SRTM mission) level. For a concise overview of GTN-G-related glacier monitoring from space as well as possible applications and related challenges, see Zemp et al. (accepted, and references therein; Part B of this work).

Guidelines and standards relating to the glacier inventory of the GLIMS initiative (mainly based on satellite images):

- Bishop, M.P., Barry, R.G., Bush, A.B.G., Copeland, L., Dwyer, J.L., Fountain, A.G., Haeberli, W., Hall, D.K., Kääb, A., Kargel, J.S., Molnia, B.F., Olsenholler, J.A., Paul, F., Raup, B.H., Shroder, J.F., Trabant, D.C., & 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. (2006). G**LIMS algorithm document.**
- Kargel, J.S., Abrams, M.J., Bishop, M.P., Bush, A., Hamilton, G., Jiskoot, H., Kääb, A., Kieffer, H.H., Lee, E.M., Paul, F., Rau, F., Raup, B., Shroder, J.F., Soltesz, D., Stearns, L., Wessels, R., &

the GLIMS Consortium (2005). **Multispectral imaging contributions to Global Land Ice Measurements from Space.** Remote Sensing of Environment, 99, 187-219.

- Rau, F., Mauz, F., Vogt, S., Khalsa, J.S., & Raup B. (2005). **Illustrated GLIMS glacier classification manual. Glacier classification guidance for the GLIMS inventory.** NSIDC, 36 pp.
- Raup, B.H., Kieffer, H.H., Hare, T.M., & Kargel, J.S. (2000). **Generation of Data Acquisition Requests for the ASTER Satellite Instrument for Monitoring a Globally Distributed Target: Glaciers.** IEEE Transactions On Geoscience and Remote Sensing, 38(2), 1105-1112.
- Raup, B.H., & Khalsa, J.S. (2007). **GLIMS analysis tutorial.** Draft, 20070522, 15 p.
- Raup, B.H., Kääb, A., Kargel, J.S., Bishop, M.P., Hamilton, G., Lee, E., Paul, F., Rau, F., Soltesz, D., Khalsa, S.J.S., Beedle, M., & 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., & Arnaud, Y. (2007). **The GLIMS Geospatial Glacier Database: a new tool for studying glacier change.** Global and Planetary Change, 56, 101-110.

3.3.2 Extending Glacier Monitoring Into the Little Ice Age and Beyond

Summary mainly based on: **Zemp, M.**, Zumbühl, H.J., Nussbaumer, S.U., Masiokas, M.H., Espizua, L.E. & Pitte, P. (subm.). **Extending glacier monitoring into the Little Ice Age and beyond.** PAGES news, 19(2).

In view of climate-change related glacier studies, one of the key issues is the comparison of the pre-industrial ‘natural’ glacier variability with the historical fluctuations in order to assess corresponding rates and acceleration of changes (Solomina, Haeberli, Kull, & Wiles, 2008). Regular observations of glacier front variations have been carried out since the late 19th century (WGMS, 2008a). Together with the positions of the moraines of the LIA, these observations document glacier fluctuations since industrialization. The in-situ observations have been compiled and published in standardized formats by and made digitally available through the international glacier monitoring organizations (WGMS 2008b, and earlier volumes). Information on glacier fluctuations before the onset of regular in-situ measurements have to be reconstructed from moraines, early photographs, drawings, paintings, prints, maps, written documents, and using a wide range of dating methods. Corresponding extensive research has been carried out and published in order to reconstruct the fluctuations of glaciers through the LIA and Holocene (e.g., Zumbühl 1980; Karlén 1988; Luckman 1993; Nicolussi and Patzelt 2000; Holzhauser, Magny, and Zumbühl 2005; Nussbaumer, Zumbühl, and Steiner 2007; Masiokas et al. 2009; Nesje 2009; Holzhauser 2010). However, the majority of corresponding data is not available to the scientific community, which presented a challenge to the reproducibility and direct comparison of the results. In Zemp et al. (subm.), we present a first approach towards the standardization of reconstructed Holocene glacier front variations, as well as the integration of the corresponding data series into the database of the WGMS, within the framework of the GTN-G.

The standardized compilation of direct front variation measurements is straightforward: besides the quantitative or qualitative change in glacier front position determined between two points in time, information is required relating to survey dates and methods as well as to the measurement accuracy. The reconstruction of front positions and the corresponding dating is much more complex and often based on multiple sets of evidence. In addition to the uncertainty in the determination of the spatial location of the glacier terminus, determination in time has to be considered, too. The article presents a concept for the integration of reconstructed front variations into the relational glacier database of the WGMS, as jointly elaborated and tested by experts of both natural and historical sciences. The database concept was developed based on reconstruction series of 15 glaciers in Europe (8 in western/central Alps and 7 in southern Norway) and 11 glaciers in the Argentinean portion of the southern Andes. The glacier reconstructions are based on the evaluation of pictorial, cartographical, and written documents, in accordance with data from preserved moraines (Nussbaumer & Zumbühl, 2011; Nussbaumer, Zumbühl, & Steiner, 2007; Tribolet, 1998; Zumbühl, 1980; Zumbühl & Holzhauser, 1988; Zumbühl, Messerli, & Pfister, 1983), including dendro-geomorphological and radiocarbon dating (Espizua, 2005; Espizua & Pitte, 2009; Masiokas et al., 2009). Among these glaciers, the Unterer Grindelwaldgletscher (central Swiss Alps) contains the best-documented series, with a total number of about 400 historical documents (Steiner, Zumbühl, & Andreas Bauder, 2008; Zumbühl, 1980).

Reconstructed glacier front variations are the key to the past in order to extend the direct measurements of the 20th and late 19th century to the moraines of the LIA and further into the Holocene. A standardized compilation and free dissemination of reconstructed as well as directly measured glacier fluctuations is of benefit to both data providers and users. Storage within the international glacier databases guarantees the long-term availability of the data series and increases the visibility of the scientific research which – in historical glaciology – is often the work of a lifetime. The compilation and dissemination of glacier fluctuations in a standardized and digital manner facilitate the comparison between glaciers as well as between different methods and opens the field for numerous scientific studies and more general applications. The presented extension of WGMS databases in order to integrate reconstructed front variations and the newly available data series from southern Norway, the Alps and the southern Andes represents a first step towards a worldwide compilation and free dissemination of standardized LIA and Holocene glacier fluctuations within the internationally coordinated glacier monitoring.

3.3.3 Glossary of Glacier Mass Balance and Related Terms

Summary mainly based on: Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A.A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Möller, M., Nicholson, L. & **Zemp, M.** (2011). **Glossary of Glacier Mass Balance and Related Terms.** IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris.

The first point measurements of mass balance were made as early as 1874 on Rhonegletscher, Switzerland. Chen and Funk (1990) were able to recover these point measurements and calculate glacier-wide annual mass-balance for 1884–85 to 1908–09 from the earlier literature (Mercanton, 1916). Unbroken series of point measurements at two sites on Claridenfirn, Switzerland, began in 1914 and continue today. Ahlmann (1935; 1939) was a pioneer in the use of what are now regarded as 'traditional' mass-balance methods. The longest continuous, modern series of annual measurements of glacier-wide mass balance was begun on Storglaciären, Sweden, in 1945–1946, followed by measurements on Taku Glacier (mainly in accumulation area) in south-eastern Alaska, Storbreen in Norway, and a growing number of glaciers in the Alps, western North America and other glacierized regions. As more measurement programs were initiated, it became clear that a uniform approach, as to both methods and terminology, was needed if comparisons were to be accurate and meaningful.

Widely used methods of 'traditional' measurement are presented by Østrem and Brugman (1991) and also by Kaser, Fountain, and Jansson (2003). Hubbard and Glasser (2005) describe glaciological field methods more generally. An early proposal for uniform usage in the study of mass balance came from Meier (1962). The terms and the organizing framework of that paper provoked considerable interest and discussion, and evolved into a consensus which was published as UNESCO/IASH (1970), although the source most often cited is Anonymous (1969), a digest of the UNESCO/IASH recommendations which appeared in the Journal of Glaciology. Some supplementary material, discussed below, appeared as UNESCO/IASH (1973). Anonymous (1969), while having no formal status, soon became the de facto standard for the presentation of mass-balance data. Although Anonymous (1969) has served glaciology well for 40 years, there is widespread agreement on the need for a new look at terminology. As a consequence, the IACS approved in principle the creation of a *Working Group on Mass Balance Terminology and Methods*. This working group tackled – as a first task – the publication of a new *Glossary of Glacier Mass Balance and Related Terms* (Cogley et al., 2011), in which we aim to update and revise what has long been the actual standard of mass balance terminology (Anonymous (1969). The new Glossary reflects changes in practice with conventional measurement tools, and also in what is possible with the wide range of new tools which were not available in the 1960s, in particular those now available for the measurement of ice-sheet mass balance. The Glossary includes commentaries, particularly on problematic usage, with recommendations where appropriate.

The new Glossary by Cogley et al. (2011) consists of a number of introductory chapters which cover the historical background of glacier mass balance as well as of its terminological practice, formulations, and units of measure; together with chapters on the reporting of mass balance data, as well as on departures from Anonymous (1969) and the format of the Glossary. These chapters are followed by the actual glossary which contains more than 450 articles. Each article in the body of the Glossary begins with a bold-font head term – the word or phrase that is about to be defined. The head term may be qualified to explain what part of speech (e.g., adjective, noun, and verb) it is. In a few cases a recommended algebraic symbol, selected with the aim of increasing clarity, is given after the head term. The head term is followed by a definition paragraph, consisting usually of a single noun phrase or sentence giving the essence of the meaning of the head term. The definition paragraph may be followed by one or more paragraphs of commentary or background information. When the head term has more than one distinct meaning, the distinct definitions are numbered. Some head terms, for example *Mass Balance* and *Time System*, have nested subheadings for closely related terms. Italicized words or phrases are cross references to other articles in the Glossary. An example is here given for the article *Annual Mass Balance* (Table 3.1).

Annual mass balance b_a (point), B_a (glacier-wide)
The sum of *accumulation* and *ablation* over the *mass-balance year*, equivalent to the sum of *annual accumulation* and *annual ablation*, and also to the sum of *winter mass balance* and *summer mass balance* where winter and summer are well-differentiated; that is, $$b_a = c_a + a_a = b_w + b_s .$$ For reasons explained more fully under *Net mass balance*, the term annual mass balance replaces the formerly distinct terms “annual balance” and “net balance”, which were used in the *fixed-date system* and the *stratigraphic system* respectively (Anonymous 1969; *Appendix A*). The adjective “annual” describes the time span of the mass-balance measurement more adequately than the adjective “net”, which does not refer to a time period but rather to the mass that is remaining after all deductions (here ablation) have been made.

Table 3.1 Excerpt from the Glossary of *Glacier Mass Balance and Related Terms* (Cogley et al., 2011) defining the article *Annual Mass Balance*. In the explanatory text, other articles covered by the Glossary are marked in italic type.

The purpose of the Glossary is not to impose awkward constraints on the evolution of glaciological usage, but rather to promote clarity and reduce ambiguity in the communication of information about glacier mass balance, as well as to provide a range of useful ancillary material (cf. Cogley 2010). For the monitoring of glacier mass balance within the GTN-G, the new Glossary is a valuable contribution, especially because it is not just a theoretical concept but rather a reference work by and for practicing glaciologists.

3.3.4 Recommendations for the Compilation of Glacier Inventory Data from Digital Sources

Summary mainly based on: Paul, F., Barry, R.G., Gogley, J.G., Frey, H., Haeberli, W., Ohmura, A., Ommanney, S.C.L., Raup, B., Rivera, A. & **Zemp, M.** (2009). **Recommendations for the compilation of glacier inventory data from digital sources.** Annals of Glaciology, 50(53), 119-126.

There still does not exist a complete detailed inventory covering all glaciers of the world. The importance of such a compilation is, however, growing in response to the need for regional to global assessments of climate change impacts on glaciers, and its effects on global sea level rise, regional hydrologic regimes and landscape evolution, and local hazard situations. Certain parts of the original recommendations designed for glacier inventories mainly based on aerial photographs and topographic maps (UNESCO 1970; Müller, Caflisch, and Müller 1977) no longer apply, as techniques have changed (e.g. punch cards are no longer in use for data processing), the source material is now digital and the focus is now on climate change impacts. This has motivated the decision to compile a new set of recommendations, published by Paul et al. in 2009, by which we aim to offer support in the efficient compilation of glacier inventory data from digital sources (i.e., satellite images and digital terrain models) in line with the standards set in the former UNESCO manuals for the WGI (WGMS, 1989).

The most important changes offered by this document, as compared to previous manuals, is that it gives access to modern geo-information techniques that enable the automated creation of detailed glacier inventory data from glacier outlines and digital terrain models. Once glacier entities are defined and an appropriate digital elevation model is available, several possibilities exist to derive the inventory data (e.g., minimum, maximum and mean elevation; mean slope and aspect) for each glacier from digital intersection of both datasets. Compared to the former manual methods, the new grid-based statistical calculations are very fast and reproducible. However, the methods applied in this way result in parameters that differ from those obtained previously and thus cannot be compared directly. As such, mean slope used to be calculated from the elevation range and the length of the central flowline in the former inventory (WGMS, 1989) and is now computed from the digital elevation model as the mean slope of all grid cells within the glacier outline. The second important difference is that two-dimensional (2-D) glacier outlines in a digital vector format are now used in addition to the point information available in the former inventory (WGMS, 1989). While the 2-D outlines strongly facilitate assessment of glacier changes, rules have to be applied that allow the clear identification of glacier entities independent of the geographic region or the data source (e.g., aerial photography or satellite imagery).

The major aim of this contribution is to help in standardizing the related calculations to enhance the integrity of the GLIMS database. The recommendations were prepared by a working group and also contribute to the *ESA* project *GlobGlacier*. The document follows the former UNESCO manual for the production of the WGI published in 1970, identifies the potential pitfalls, and describes the differences as compared to former methods of compilation. The paper provides generic guidelines on the perennial snow and ice masses to be registered, source material suitable for the compilation of a digital glacier inventory, and data organization for the (ideally automated) computation of a minimal set of required parameters which are glacier identification, coordinates, date, surface area, length, minimum, maximum, mean and median elevation, as well as mean orientation and slope. The most time-consuming, but nevertheless important, parameter is the (still) manual digitizing of glacier length. Besides the basic parameters, guidelines for other useful parameters are added for practical purposes. In view of the rapid technological development and the explosion of freely available datasets in the recent past, it is assumed that parts of the recommendations will have to be updated regularly. It is hoped that the recommendations by Paul et al. (2009) will contribute to completion of a detailed world glacier inventory in the near future and result in a wealth of scientific applications (e.g., Haeberli and Hoelzle 1995; Linsbauer et al. 2009; Berthier et al. 2010; Radić and Hock 2011).

4 Glacier Distribution and Changes at Local, Mountain, and Global Scale

4.1 Context of the Following Contributions

The present chapter deals with the implementation of the integrated multi-level monitoring strategy of GTN-G. It summarizes the results of eight papers that – as a unit – cover (almost) the entire spectrum of applied methods and spatial scales (Table 4.1). This includes recent examples of basic glacier monitoring for process understanding and uncertainty assessments at local (glacier) scale based on in-situ observations and remote sensing at Storglaciären in Sweden (Koblet et al., 2010; Zemp, Jansson, et al., 2010). Glacier distribution and changes are assessed over entire mountain ranges for the European Alps (Zemp, Haeberli, Hoelzle, & Paul, 2006; Zemp, Hoelzle, & Haeberli, 2007; Zemp, Paul, Hoelzle, & Haeberli, 2008), and for all of Europe (Zemp, Andreassen, et al., 2010). For the recent distribution and changes since the LIA maximum extents, in-situ and remote sensing observations as available from GTN-G were analyzed in combination with extensive reviews of the corresponding literature. For the projection of future glacier change based on climate scenarios, numerical modeling studies were reviewed for the majority of mountain ranges in Europe (Zemp, Andreassen, et al., 2010) together with own simulations for the European Alps (Zemp, Haeberli, Hoelzle, & Paul, 2006; Zemp, Hoelzle, & Haeberli, 2007). On the global scale, glacier distribution and changes were assessed based on all available in-situ and remote sensing observations including a review of the related literature (WGMS, 2008a). The worldwide glacier mass balance monitoring network and the application of its results were reviewed in more detail (Zemp, Hoelzle, & Haeberli, 2009).

Paper	Applied Methodology				Spatial Scale		
	in-situ observation	remote sensing	numerical modeling	literature review	local	mountain	global
Koblet et al. (2010)		X			X		
Zemp, Jansson, et al. (2010)	X	X		X	X		
Zemp et al. (2008)	X	X				X	
Zemp, Hoelzle, and Haeberli (2007)			X			X	
Zemp et al. (2006)	X	X	X			X	
Zemp, Andreassen, et al. (2010)				X		X	
WGMS (2008a)	X	X		X			X
Zemp, Hoelzle, and Haeberli (2009)	X			X			X

Table 4.1: Overview of papers summarized in the current chapter according to the applied methodology and the spatial scale.

4.2 Re-analysis of Multi-temporal Aerial Images of Storglaciären, Sweden (1959−1999) - Part 1: Determination of Length, Area, and Volume Changes

Summary mainly based on: Koblet, T, Gärtner-Roer, I., **Zemp**, M., Jansson, P., Thee, P., Haeberli, W. & Holmlund, P. (2010). **Re-analysis of multi-temporal aerial images of Storglaciären, Sweden (1959−99) - Part 1: Determination of lenth, area, and volume changes.** The Cryosphere, 4, 333-343.

Storglaciären, located in the Kebnekaise massif in northern Sweden, has a long history of glaciological research. Early photo documentations date back to the late 19th century (Holmlund, Karlén, & Grudd, 1996). Measurements of front position variations and distributed mass balance have been carried out since 1910 and 1945/46, respectively (Holmlund, Karlén, & Grudd, 1996; Schytt, 1981). In addition to these in-situ measurements, aerial photographs have been taken at decadal intervals since the beginning of the mass balance monitoring program and were used to produce topographic glacier maps (Holmlund, 1996). Inaccuracies in the maps were a challenge to early attempts to derive glacier volume changes and resulted in major differences when compared to the direct glaciological mass balances (Albrecht, Jansson, & Blatter, 2000; Holmlund, 1987).

In the study by Koblet et al. (2010), we re-analyze the original aerial photographs of 1959, -69, -80, -90, and -99, applying a consistent photogrammetric processing strategy for all survey years. The resulting digital elevation models and orthophotos are used to determine and analyze length, area, and volume changes of Storglaciären. The main objective of this study is to find out whether a thorough re-analysis of existing aerial photographs allows for a more accurate quantification of glacier changes. Given the limited number of long volumetric mass balance series, the quality control of existing data is very important. Therefore, the results are discussed including a qualitative and quantitative assessment of related uncertainties, in view of results from this and earlier studies as well as resulting consequences for future research.

Based on this new dataset, changes in Storglaciären in length, area, and volume are computed for the time periods between these surveys. The glacier lost 15 and 11×10^6 m^3 from 1959–69 and 1969–80, respectively. In the following two decades (1980–90, 1990–99) a partial regain of the lost ice volume of 5 and 2×10^6 m^3 was found. Over the entire period from 1959–99, Storglaciären lost an ice volume of 19×10^6 m^3. Averaged over the glacier area, this corresponds to a total ice thickness loss of 5.7 m, or to a mean annual ice loss of 0.14 m. The glacier reacted to this volume change with a slowing of its retreat, and ultimately to pseudo-stationary conditions in the last observation period (1990–99).

The uncertainty assessment shows that elevations of all the *Digital Elevation Models* (DEMs) are systematically too low by a few meters, but with standard errors of less than one meter. The DEM of 1980 performed less well than the other DEMs. Statistical comparisons of the glacier changes with the 'noise' in non-glacierized terrain prove the general significance of the results, with ablation areas performing better than accumulation areas. Again, the results including the DEM of 1980 perform less well than the others. From the first to the last observation period, the absolute signal decreases and challenges the basic dataset and methodology. The resulting length changes fit well to the cumulative in-situ observations. Only in the first decade (1959–69) do larger differences occur, which are probably due to the different measurement approaches. The absolute changes in area are small, but the relative changes differ between this and earlier studies. This is attributed to different interpretations of the glacier margins, especially in regions with shadow and/or snow cover. The major differences from earlier studies (Albrecht, Jansson, & Blatter, 2000; Holmlund, 1987; 1996), however, lie in the resulting volume changes of the glacier. Although difficult to quantify, we see the main cause to be the heterogeneous methodology of these earlier studies, which derived volume changes indirectly from topographic glacier maps of various origins. The resulting volume changes from the study by Koblet et al. (2010) – although not free of errors – are based on a consistent re-processing of the original material, come with a sound uncertainty assessment, and allow a comparison with the in-situ mass balance measurements (cf. Zemp, Jansson, et al. 2010).

The resulting data emphasize the importance of aerial photographs in glacier research, especially for quantifying length, area, and volume changes as well as for crosschecking in-situ measurements. Beyond that, the available DEMs and orthophotos can be used for investigations on the surrounding glaciers and for geomorphological mapping purposes in the Tarfala Valley. Looking into the (scientific) future, we would like to stress the importance of such decadal flight campaigns. We highly recommend compiling a new, high-resolution and high-precision dataset that serves as a master dataset for a new accuracy assessment, including independent spatial data. In this context, the spatial distribution and visibility of the ground control points around Storglaciären have to be improved and the date of the survey should be as close as possible to the in-situ annual mass balance measurements. With such a dataset, glacier changes since 1959 can be quantified with greater accuracy and reliability. In addition, more analyses using the multi-temporal DEMs in combination with reference data and glaciological field measurements should be performed at the Storglaciären test site. By the application of modern techniques such as airborne laser scanning (cf. Geist, Lutz, and Stötter 2003; Joerg, Morsdorf, and Zemp 2010), the number of problems related to shadows and snow cover, influencing the final data product, can be reduced.

4.3 Re-analysis of Multi-temporal Aerial Images of Storglaciären, Sweden (1959−1999) - Part 2: Comparison of Glaciological and Volumetric Mass Balances

Summary mainly based on: **Zemp**, M., Jansson, P., Holmlund, P., Gärtner-Roer, I., Koblet, T., Thee, P. & Haeberli, W. (2010). **Re-analysis of multi-temporal aerial images of Storglaciären, Sweden (1959−99) - Part 2: Comparison of glaciological and volumetric mass balances.** The Cryosphere, 4, 345-357.

Changes in glacier mass are a key element of glacier monitoring, providing important information for assessing climatic changes, water resources, and sea level changes (Kaser, Cogley, Dyurgerov, Meier, & Ohmura, 2006; Zemp, Hoelzle, & Haeberli, 2009). The available dataset of in-situ glacier mass balance measurements covers the past six decades. The majority of these data series consists of just a few observation years. There are only 12 mass balance programs with continuous observations dating back to 1960 or earlier (Zemp, Hoelzle, & Haeberli, 2009), including Storglaciären, located in the Kebnekaise massif in northern Sweden, with the longest record of glacier mass balance and one of the densest observation networks. The homogenization of these observations is gaining importance with the increasing time length of the data series (e.g., Thibert et al. 2008; Huss, Bauder, and Funk 2009; Fischer 2010).

Annual glacier mass balance measurements based on the direct glaciological method (cf. Østrem and Brugman 1991) are thus combined, in the ideal case, with decadal volume change assessments from geodetic surveys in order to assess random and systematic errors of both methods (Fountain, Jansson, Kaser, & Dyurgerov, 1999; Haeberli, 1998; Hoinkes, 1970). Storglaciären has been surveyed by aerial photography about once every decade (Holmlund, 1996). Maps were made based on these aerial photographs to determine the glacier area needed for mass balance calculations (Holmlund, Jansson, and Pettersson 2005, Tarfala Research Station data) and to analyze the changes in surface topography (Holmlund 1987; 1996). However, the comparison of volumetric mass balances derived from these digitized topography maps (of 1959, -69, -80, -90) with cumulative mass balance measurements shows major discrepancies, with maximum differences of half a meter per year (1969–80), as already noted by Albrecht, Jansson, and Blatter (2000). In order to overcome the problems related to the various existing maps and the methods used for deriving volume changes of Storglaciären, we re-processed diapositives of the original aerial photographs of 1959, -69, -80, -90, and -99 based on a consistent photogrammetric processing for all survey years. Details on the study site, methodology, resulting DEMs and orthophotos, and derived changes in length, area, and volume are published in Koblet et al. (2010).

In Zemp, Jansson, et al. (2010), we compare the new volumetric mass balances with the glaciological mass balances for the periods of the aerial surveys. In addition, we summarize uncertainties related to both methods under consideration of all related previous studies and estimates for uncertainties related to the major potential sources of error, such as in-situ and remote sensing methods applied, density assumptions, differences in survey dates and reference areas, internal ablation and accumulation, superimposed ice, and flux divergence. The paper concludes with a number of recommendations for the mass balance monitoring program at Storglaciären that might hopefully be useful of other long-term monitoring programs as well.

The volumetric mass balances are in good agreement with the glaciological data. The absolute differences between volumetric and the glaciological mass balances are 0.8 m w.e. in the first and 0.3 m w.e. or less in the other three decadal survey periods. These deviations can be reduced in most periods by applying corrections for systematic uncertainties such as differences in survey dates and reference areas or accounting for internal ablation. In contrast, accounting for internal accumulation based on the study by Schneider and Jansson (2004) systematically increases the mismatch. This suggests that either the effect of the internal accumulation is overestimated or that there is another systematic error not yet considered. However, the mean annual differences between such a “best estimate” glaciological mass balance, which corrects the official series by all directional uncertainties, and the volumetric mass balance, corrected for systematic uncertainties, are less than about 0.1 m w.e. a^{-1} and as such are within the order of magnitude of the stake and pit reading error. From the present study we conclude that the new volumetric mass balances fit well overall with the glaciological ones and confirm the excellent quality of this data series. Excluding the systematic deviations due to the issue with the internal accumulation, there is an overlap of stochastic error bars of volumetric and glaciological mass balances and, hence, no need for an adjustment of the glaciological data series. Thanks to the very dense observation network of Storglaciären, the cumulative glaciological series fits well to the decadal volumetric data in spite of the low mass balance signal. Further investigations should, however, address the better quantification of systematic error sources, such as internal accumulation, as well as the issue of the (changing) reference areas used for mass balance calculations. The study by Zemp, Jansson, et al. (2010) shows the importance of systematic and ideally uniform data processing as well as a sound uncertainty assessment in order to detect – and if necessary correct – systematic errors in the measurements. A next aerial survey is, therefore, overdue and should provide a new high-precision and high-resolution reference digital elevation model.

4.4 Glacier Fluctuations in the European Alps 1850–2000: an Overview and Spatio-temporal Analysis of Available Data

Summary mainly based on: **Zemp**, M., Paul, F., Hoelzle, M. & Haeberli, W. (2008). **Glacier fluctuations in the European Alps 1850–2000: an overview and spatio-temporal analysis of available data.** In: Orlove, B., Wiegandt, E. and B. Luckman (eds.): The darkening peaks: Glacial retreat in scientific and social context. University of California Press, 152-167.

The modern concept of worldwide glacier observation is an integrated and multilevel one; it aims to combine in-situ observations with remotely sensed data, understanding of process with global coverage, and traditional measurements with new technologies (Haeberli, 1998). This concept uses detailed mass and energy balance studies from just a few glaciers, together with length change observations from many sites and inventories covering entire mountain chains. Numerical models link all three components over time and space (Haeberli, 2004). The *European Union*-funded *ALP-IMP* project focused on multicentennial climate variability in the Alps on the basis of instrumental data, model simulations, and proxy data. It represented a unique opportunity to apply this glacier monitoring concept to the European Alps, where by far the most concentrated amount of information about glacier fluctuations over the past century is available.

In the paper by Zemp et al. (2008), we offer an overview of the available glacier datasets from the European Alps and analyze glacier fluctuations between 1850 and 2000. To achieve this, we analyze glacier size characteristics from the 1970s, the only time period for which a complete Alpine inventory is available (cf. WGMS 1989), and extrapolate Alpine glaciations in 1850 and in 2000 from size-dependent area changes as derived from the *Swiss Glacier Inventory* (Kääb, Paul, Maisch, Hoelzle, & Haeberli, 2002; Maisch, Wipf, Denneler, Battaglia, & Benz, 2000; Paul, 2007; Paul, Kääb, Maisch, Kellenberger, & Haeberli, 2002). We go on to examine mass balance and front variation series for the insight they provide into glacier fluctuations, the corresponding acceleration trends, and regional distribution patterns at an annual resolution. Finally, we discuss the representativeness of these recorded fluctuation series for all the Alpine glaciers and draw conclusions for glacier monitoring.

In the European Alps, the growth of the glacier monitoring network over time has resulted in an unprecedented glacier dataset with excellent spatial and temporal coverage. The WGMS compiled information on spatial glacier distribution from approximately 5,150 Alpine glaciers (WGMS 1989), and fluctuation series from more than 670 of these glaciers (i.e., more than 25,350 annual front variation and 575 annual mass balance observations at the time of this analysis) dating back to 1850 (WGMS 2008b, and earlier volumes). National inventories are able to provide complete Alpine coverage for the 1970s, when the glaciers covered a total area of 2,909 km^2. This inventory, together with digital outlines from the Swiss Glacier Inventory, is used to extrapolate total Alpine glacier-covered areas in 1850 and 2000 which amount to about 4,470 km^2 and 2,270 km^2, respectively. This corresponds to an overall loss from 1850 to the 1970s of 35%, and almost 50% by 2000. Annual mass balance and front variation series provide a better time resolution than the inventories over the past 150 years. During the general retreat, intermittent periods of glacier re-advances in the 1890s, 1920s and 1970–1980s can still be seen (cf. Patzelt 1985). Increasing mass loss, rapidly shrinking glaciers, disintegrating and spectacular tongue retreats are clear signs of the atmospheric warming observed in the Alps during the last 150 years and the acceleration observed over the past two decades (e.g., Paul et al. 2004; Zemp et al. 2005). However, in the short term or at a regional scale, glaciers show a highly individual variability. Glacier behavior depends not only on regional climate but also on local topographic effects which complicate the extraction of the climate signal from glacier fluctuations (cf. Kuhn et al. 1985; Vincent et al. 2004).

While inventory data contain information on spatial glacier distribution at certain times, fluctuation series provide temporal information at specific locations. Continuity of fluctuation series and the assessment of their representativeness for the entire mountain range (cf. Paul and Haeberli 2008) are thus most relevant for the planning of glacier monitoring. Furthermore, modeling should be enhanced and integrated into monitoring strategies (e.g., Oerlemans et al. 1998; Oerlemans 2001; Paul et al. 2008). It is of major importance to continue with long-term fluctuation measurements and to extend the series back in time with reconstructions of former glacier geometries.

4.5 Distributed Modeling of the Regional Climatic Equilibrium Line Altitude of Glaciers in the European Alps

Summary mainly based on: **Zemp**, M., Hoelzle, M. & Haeberli, W. (2007). **Distributed modeling of the regional climatic equilibrium line altitude of glaciers in the European Alps.** Global and Planetary Change, 56, 83-100, doi:10.1016/j.gloplacha.2006.07.002.

The equilibrium line altitude of a glacier is a theoretical line which defines the altitude at which annual accumulation equals ablation. It represents the lowest boundary of the climatic glacierisation and, therefore, is an excellent indicator of climate variability (Kuhn 1981; Ohmura, Kasser, and Funk 1992; Lie, Dahl, and Nesje 2003a; 2003b). In the work by Zemp, Hoelzle, and Haeberli (2007), we present a simple approach that is able to model the glacier distribution at high spatial resolution (about 100 m) over entire mountain ranges. Furthermore, the sensitivity of the Alpine glacierisation to changes in temperature and precipitation is investigated, and the possible impact of a climate change scenario on Alpine glacierisation in the decades to come is demonstrated. To achieve this, a simple approach for modeling the glacier distribution at high spatial resolution is introduced, using a minimum of input data. An empirical relationship between precipitation and temperature at the equilibrium line altitude is derived from direct glaciological mass balance measurements (WGMS 2009, and earlier issues). Using geographical information systems and a digital elevation model, this relationship is then applied over a spatial domain, to a so-called distributed modeling of the regional climatic equilibrium line altitude and the corresponding climatic accumulation area for 1971 to 1990 over the entire European Alps.

The sensitivity study shows that for Alpine glaciers, a change in 6-month summer temperature by ±1 °C would be compensated for by an annual precipitation increase/decrease of about 25%, which is in good agreement with results by Kuhn (1981), Braithwaite and Zhang (2000), and Oerlemans (2001). The modeled climatic accumulation area of 1971–1990 agrees well with accumulation areas of mapped glacier outlines from the 1973 *Swiss Glacier Inventory* (Kääb, Paul, Maisch, Hoelzle, & Haeberli, 2002; Maisch, Wipf, Denneler, Battaglia, & Benz, 2000; Paul, 2007; Paul, Kääb, Maisch, Kellenberger, & Haeberli, 2002) and covers an area of 3,059 km^2 over the entire Alps. As the climatic accumulation area is simply the terrain above the regional climatic equilibrium line altitude, it does not distinguish between glacier surface and ice-free rock walls. In a first order approach, this can be corrected by applying of the slope-dependent function of glacier fraction to the modeled climatic accumulation area. The thus corrected climatic accumulation area equals 1,950 km^2 and corresponds to an accumulation area ratio of 0.67 (cf. WGMS 2009) of the measured total Alpine glacier area in the 1970s (WGMS, 1989), which was 2,909 km^2. Assuming a warming of 0.6 °C between 1850 and 1971−90 leads to a mean rise of the regional climatic equilibrium line altitude of 75 m, and a corresponding climatic accumulation area reduction of 26%. This latter value is somewhat lower than the loss in glacier area (35%) as estimated from glacier inventory data from 1850 and the 1970s (cf. Zemp et al. 2008), and suggests that either the model is not perfectly able to reproduce the area loss between 1850 and the 1970s, or that a rise in temperature by 0.6 °C cannot completely explain the corresponding glacier shrinkage. A further rise in temperature of 3 °C accompanied by an increase in precipitation of 10% leads to a further mean rise of the regional climatic equilibrium line altitude of about 340 m and reduces the climatic accumulation area of 1971–1990 by about 75%. As a consequence, many regions become ice-free and remaining accumulation areas of glaciers diminish greatly and disintegrate.

The presented approach is an excellent complement to distributed mass balance models (e.g., Klok and Oerlemans 2002; Paul et al. 2008). As the presented distributed model requires only a minimum amount of input data to compute the regional climatic equilibrium line altitude over the entire Alps, distributed mass balance models can then be used to account for further important components of the energy balance (e.g., solar radiation, albedo, turbulent fluxes, mass balance-altitude feedback) and local, topographic effects (e.g., shading, avalanches, snowdrift) within individual catchments. Furthermore, distributed modeling of the regional climatic equilibrium line altitude can potentially contribute to the current efforts to include glacier altitude-area distribution of past, present and future glacier states in regional climate models (cf. Kotlarski and Jacob 2005).

4.6 Alpine Glaciers to Disappear within Decades?

Summary mainly based on: **Zemp**, M., Haeberli, W., Hoelzle, M. & Paul, F. (2006). **Alpine glaciers to disappear within decades?** Geophysical Research Letters, 33, L13504, doi:10.1029/2006GL026319.

In the study by Zemp et al. (2006), we apply an integrated approach, combining in-situ measurements, remote sensing techniques and numerical modeling to the European Alps. These techniques allow past as well as potential evolutions of a glacier ensemble within an entire mountain chain to be assessed quantitatively. Glacier fluctuations from 1850 to 2000 are analyzed from earlier (Maisch, Wipf, Denneler, Battaglia, & Benz, 2000; WGMS, 1989) and recent inventories (Kääb, Paul, Maisch, Hoelzle, & Haeberli, 2002; Paul, 2007; Paul, Kääb, Maisch, Kellenberger, & Haeberli, 2002), together with compilations on past glacier fluctuations (WGMS, 2008b), and earlier volumes). Potential future area changes for the entire Alps are estimated using two independent methods. The first method is a purely empirical one that relates documented rates of area change for altitudinal bands to scenarios of glacier shrinking. The second approach (based on Zemp, Hoelzle, and Haeberli 2007) is a statistically calibrated and distributed model of glacier equilibrium line altitude that utilizes an empirical relation between 6-month summer air temperature and annual precipitation at the equilibrium line altitude. With this model, the climatic accumulation area is computed over the entire Alps for the reference period (1971–90) and for the entire range of temperature and precipitation scenarios for the 21st century, as published by IPCC (2001). Finally, past, present and future ice volumes are calculated by multiplying reconstructed/measured mass balance values with the average surface area of a given time period.

Alpine glaciers lost almost 50% in area from 1850 to 2000. The area reduction between 1975 and 2000 is about 22%, mainly occurring after 1985. Disintegration and 'downwasting' have been predominant processes of glacier decline during the most recent past. The scenarios of future area losses illustrate that the scenario of 'accelerated loss' (area reduction for the period 1975 to 2000) would drastically reduce Alpine glacier areas within this century and that the scenario of extreme ice loss (using doubled 1985 to 2000 loss rates) would cause most of the presently existing glaciers in the Alps to disappear within decades as large parts of the ice is located below 3,000 m a.s.l. The impact on glacier areas as related to scenarios of temperature and precipitation show that a 3 °C warming of summer air temperature would reduce the currently existing Alpine glacier cover by some 80%, or up to 10% of the glacier extent of 1850. In the event of a 5 °C temperature increase, the Alps would become almost completely ice-free. Annual precipitation changes of ±20% would modify such estimated percentages of remaining ice by a factor of less than two. Volume loss between 1975 and 2000 is calculated from cumulative mass balance of -12 m w.e. over a mean Alpine glacier area of 2,590 km^2 to be 30 km^3. Total Alpine ice volumes can be estimated roughly as 200 km^3 in 1850, 105 km^3 in 1975 and 75 km^3 in 2000 (cf. Farinotti et al. 2009). The average mass balance of -2.5 m w.e. in the extreme year 2003 eliminated an estimated 8% of the remaining Alpine ice volume within one single year (cf. Zemp, Kääb, et al. 2005). Such extremely hot and dry summers (cf. Schär et al. 2004) not only induce strong positive feedbacks, but also eliminate increasing percentages. It is likely that five rather than ten repetitions within the coming decades of conditions as in 2003 would bring about the scenario of widely deglaciated Alps. By simply looking at the evolution of glaciers in the mountain ranges of the world, coming generations will be able to define and to physically see which scenario of climate change has taken place.

4.7 Glacier Distribution and Changes in Europe

Summary mainly based on: **Zemp, M.**, Andreassen, L.M., Braun, L., Chueca, J., Fischer, A., Hagen, J.O., Hoelzle, M., Jansson, P., Kohler, J., Meneghel, M., Stastny, P. & Vincent, C. (2010). **Glacier and Ice Caps**. In: Voigt, T., Füssel, H.-M., Gärtner-Roer, I., Huggel, C., Marty, C. & **Zemp, M.** (eds.). Impacts of climate change on snow, ice, and permafrost in Europe: Observed trends, future projections, and socio-economic relevance. European Topic Centre on Air and Climate Change, Technical Paper, 2010 (13), 46-65.

There is rising concern (also) among policy- and decision-makers about the impacts of recent and projected changes in climate on the cryosphere and of the societal relevance of these changes. As a consequence, the *European Topic Centre on Air and Climate Change* in close collaboration with the *Department of Geography* of the *University of Zurich* and the *Swiss Federal Institute for Forest, Snow and Landscape Research* produced a technical paper providing information on present state and changes of Europe's cryosphere to the *European Environment Agency* of the *European Union*. This report by Voigt et al. (2010) aims to serve the information needs of a wider audience, including policy-makers at the European, national and sub-nation level, non-governmental organizations, and the wider public, by providing understandable key messages and graphs supported by thorough and more technical reviews of the corresponding scientific state of knowledge. The review paper by Zemp, Andreassen, et al. (2010) was prepared in collaboration with active glaciologists from all over Europe and provides a review of distribution, changes since the LIA, and an outlook on the 21st century of European glaciers and ice caps (outside Greenland).

Due to their proximity to melting conditions, glaciers are one of the most reliable natural indicators for climatic changes (GCOS, 2004; GTOS, 2008). In the second half of the 20th century, European glaciers and ice caps (outside Greenland) covered a total of about 54,000

km^2 (WGMS, 1989) distributed in Svalbard (68%), Iceland (21%), Scandinavian Peninsula (6%), Alps (5%), and the Pyrenees (<1%). The total volume of glaciers can only be roughly approximated. Current rough estimates by Radić and Hock (2010) based on the above (area) data come to an ice volume of about 15,500 km^3. This corresponds to a potential sea level rise of about 40 mm, of which the vast majority is located in Svalbard (26 mm) and Iceland (12 mm).

The LIA moraines that formed between the mid 18th and the mid 19th century mark the maximum glacier extents during the past 11,000 years (the Holocene; Grove 2004; Solomina et al. 2008). The strong centennial retreat of glaciers from these LIA moraines is well documented and apparent in all European regions. In some regions, there have been intermittent periods of reduced glacier melting or even of glacier re-advance such as in the late 1970s in the Alps (Citterio et al., 2007; Patzelt, 1985; Pelfini & Smiraglia, 1988; Zemp, Paul, Hoelzle, & Haeberli, 2008) and Iceland (Sigurðsson, Jónsson, & Jóhannesson, 2007) and in the 1990s in coastal Scandinavia (Andreassen, Elvehøy, & Kjøllmoen, 2005). Glacier melt seems to be strongest in the European Alps. There, more than half of the ice-covered area has disappeared since 1850 (Zemp, Haeberli, Hoelzle, & Paul, 2006; Zemp, Paul, Hoelzle, & Haeberli, 2008); the average annual ice thickness loss since 2000 has been above one meter. European glacier changes since the LIA have been driven mainly by increased summer air temperatures (e.g., Oerlemans 1994; Dowdeswell et al. 1997; Vincent 2005; Sigurðsson, Jónsson, and Jóhannesson 2007; Zemp et al. 2008) with secondary effects from variations in winter precipitation (e.g., Patzelt 1985; Vincent 2005; Wanner et al. 2005; Andreassen, Elvehøy, and Kjøllmoen 2005). Both are influenced by atmospheric and oceanic circulation patterns (e.g., Hoinkes 1968; Hanssen-Bauer and Førland 1998; Chen and Hellström 1999; Nesje, Lie, and Dahl 2000; Wanner et al. 2001; Uvo 2003; Huss et al. 2010). Further factors affecting the increasingly negative mass balances in most regions are most probably the (re-) brightening of the atmosphere (Huss, M. Funk, & Ohmura, 2009; Ohmura, Andreas Bauder, H. Müller, & Kappenberger, 2007), extension of the ablation period (e.g. Vincent et al. 2004; Bocchiola and Diolaiuti 2009), and reinforcing effects such as dust-related darkening or melt-induced elevation lowering of glacier surfaces (Oerlemans, Giesen, & Van Den Broeke, 2009; Paul, Machguth, & Kääb, 2005).

Climate change scenarios for the 21st century (IPCC, 2007; Van Der Linden & Mitchell, 2009) suggest a continued increase in global mean air temperature (without policy measures) by 1.4 to 5.8°C, and 2.0 to 6.3°C in Europe. Corresponding projections of precipitation patterns show a more varied picture with seasonal change rates of 1 to 5% per decade. In such scenarios, glaciers will continue to melt and may totally disappear in some mountain ranges in the coming decades (Nesje, Bakke, S. Dahl, Lie, & Matthews, 2008; Zemp, Haeberli, Hoelzle, & Paul, 2006). Available numerical model experiments on glaciers in Iceland (e.g., Aðalgeirsdóttir et al. 2006), Scandinavia (e.g., Oerlemans 1997; Nesje et al. 2008; Radić and Hock 2006; Giesen and Oerlemans 2010) and in the Alps (e.g., Haeberli and Hoelzle 1995; Zemp et al. 2006; Zemp, Hoelzle, and Haeberli 2007; Le Meur et al. 2007; Huss et al. 2007; Huss, Jouvet, et al. 2010) indicate that a further increase in regional summer air temperature by 2° C will reduce glacier area and volume by half or more of their present extents. The impact of a 1°C warming could only be offset if precipitation increased by 20% or more. Potential re-growth of glaciers in these regions would require decades of cooler and wetter conditions.

Glaciers changes in Europe already influence the local hazard situation (e.g. Huggel et al. 2010a; 2010b), the runoff from alpine catchments (e.g. Weber et al. 2010), tourism and landscape (e.g. Abegg et al. 2007), and – to a limited extent – global sea level (e.g., Radić and

Hock 2010; J. O. Hagen, Kohler, Melvold, and Winther 2003; J. O. Hagen, Melvold, Pinglot, and Dowdeswell 2003). The anticipated marked changes for the 21st century might lead to corresponding impacts without historical and Holocene precedence.

4.8 Global Glacier Changes: Facts and Figures

Summary mainly based on: WGMS (2008a). **Global Glacier Changes: facts and figures. Zemp, M.**, Roer, I., Kääb, A., Hoelzle, M., Paul, F. & Haeberli, W. (eds.), UNEP, World Glacier Monitoring Service, Zurich, Switzerland, 88 pp.

Changes in glaciers and ice caps provide some of the clearest evidence of climate change, and as such they constitute key variables for early detection strategies in global climate-related observations (GCOS, 2004; GTOS, 2008). These changes have impacts on global sea level fluctuations, the regional to local natural hazard situation, as well as on societies dependent on glacier melt water. Internationally coordinated collection and publication of standardized information about ongoing glacier changes was initiated back in 1894 (Forel, 1895). The compiled datasets on the global distribution (WGMS, 1989) and changes (WGMS 2008b, and earlier volumes) in glaciers and ice caps provide the backbone of the numerous scientific publications on the latest findings about surface ice on land (e.g. Lemke et al. 2007). Since the very beginning, the compiled data has been published by the WGMS and its predecessor organizations. However, the corresponding data tables, formats and meta-data are mainly of use to specialists.

It is in order to fill the gaps in access to glacier data and related background information that the publication by the WGMS (2008a) aims to provide a commented and illustrated global view of the available datasets related to glaciers and ice caps, their distribution around the globe, and the changes that have occurred since the maximum extents of the so-called LIA. The report starts with forewords by UNEP Executive Director Achim Steiner and by WGMS Director (at that time) Wilfried Haeberli followed by a general introduction and four chapters on glaciers and climate, global distribution of glaciers and ice caps, glacier fluctuation series, and global glacier changes. Chapter 6 summarizes regional glacier changes in New Guinea, Africa, New Zealand, Scandinavia, Central Europe, South America, Northern Asia, Antarctica, Central Asia, North America, and Arctic Islands. The Conclusions section in Chapter 7 is followed by the list of references and two appendices with full address details of the WGMS *National Correspondents* and factsheets with meta-data on available fluctuation data arranged alphabetically according to glacier names and country by country. The report was compiled in collaboration with the WGMS network of *National Correspondents* and *Principal Investigators* and reviewed by regional glacier experts.

International glacier monitoring has produced a range of unprecedented data compilations including some 36,000 length change observations and roughly 3,400 mass balance measurements for approximately 1,800 and 230 glaciers, respectively. The observation series are drawn from around the globe; however, there is a strong bias towards the Northern Hemisphere and Europe. A first attempt to compile a world glacier inventory was made in the 1970s based mainly on aerial photographs and maps. It has resulted to date in a detailed inventory of more than 100,000 glaciers covering an area of about 240,000 km^2 and in preliminary estimates, for the remaining ice cover of some 445,000 km^2 for the second half of the 20th century. This inventory task continues through the present day, based mainly on satellite images within the GLIMS initiative.

The moraines formed towards the end of the LIA, between the 17th and the second half of the 19th century, are prominent features of the landscape, and mark Holocene glacier maximum extents in many mountain ranges around the globe (Grove, 2004; Solomina, Haeberli, Kull, & Wiles, 2008). From these positions, glaciers worldwide have been shrinking significantly, with strong glacier retreats in the 1940s, stable or growing conditions around the 1920s and 1970s, and again increasing rates of ice loss since the mid 1980s. However, on a time scale of decades, glaciers in various mountain ranges have shown intermittent re-advances. When looking at individual fluctuation series, one finds a high rate of variability and sometimes widely contrasting behavior of neighboring ice bodies.

In current scenarios of climate change (cf. IPCC 2007), the ongoing trend of worldwide and rapid, if not accelerating, 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 in the coming decades. Such rapid environmental changes require that the international glacier monitoring efforts make use of the swiftly developing new technologies, such as remote sensing and geo-informatics, and relate them to the more traditional field observations, in order to better face the challenges of the 21st century.

4.9 Six Decades of Glacier Mass Balance Observations - a Review of the Worldwide Monitoring Network

Summary mainly based on: **Zemp, M.**, Hoelzle, M. & Haeberli, W. (2009). **Six decades of glacier mass balance observations - a review of the worldwide monitoring network.** Annals of Glaciology, 50(50), 101-111.

The WGMS collects and publishes mass balance data of glaciers obtained by direct glaciological and geodetic methods as a contribution to the GTN-G (WGMS, 2008b), and earlier volumes). The corresponding monitoring strategy uses glacier observations in a system of tiers (cf. Haeberli, Cihlar, and Barry 2000; Haeberli 2004). These tiers include extensive glacier mass-balance measurements within major climatic zones for improved process understanding and the calibration of numerical models (tier 2), as well as for the determination of regional volume changes within major mountain ranges using cost-saving methodologies (tier 3). Glacier front variation and global inventories are further components of the monitoring strategy but are not discussed here.

First surveys of accumulation and ablation of snow, firn and ice at individual stakes date back to the end of the 19th century and the beginning of the 20th century, for example at Rhonegletscher (Mercanton, 1916) and Silvrettagletscher (Huss, a Bauder, Martin Funk, & Hock, 2008). Annual glacier mass balance measurements made by the direct glaciological method (cf. Østrem and Brugman 1991), based on an extensive network of ablation stakes, snow pits and snow probing, were initiated in 1945 at Storglaciären, Sweden (Holmlund, Jansson, & Pettersson, 2005; Schytt, 1981). Today, six decades of annual (and partially seasonal) mass-balance data are readily available from the WGMS and have been analyzed in detail by Dyurgerov (2002; 2010) and widely used for studies of glacier changes (e.g., Dowdeswell et al. 1997; Braithwaite 2002; Dyurgerov and Meier 2005; Armstrong 2010) and related questions from hydrology (e.g. Braun, Weber, and Schulz 2000), climate change (e.g. Oerlemans and Fortuin 1992; Francou 2003; Ohmura 2006) or sea-level variation studies (e.g., Kaser et al. 2006; Raper and Braithwaite 2006; Meier et al. 2007; Steffen et al. 2010). However, due to the specific foci of these works, a sound and integrative discussion of the basic dataset and related issues is often neglected. In the paper by Zemp, Hoelzle, and Haeberli (2009), we aim to give a review of the present monitoring network, a spatiotemporal analysis of the available data and discuss important issues related to the monitoring and interpretation of glacier mass balance data.

During the six decades of glacier mass balance observation, the WGMS has compiled a dataset of more than 3400 annual mass balance measurements from 228 glaciers worldwide. The collection and free availability of these data through a purely scientific collaboration network is a great success and, at the same time, one of the reasons why the present monitoring network is unevenly distributed in comparison with the global ice coverage. The 30 reference glaciers, with continuous observation series since 1976, show an accelerated thinning with mean annual ice losses of 0.14 m w.e. (1976 to 85), 0.25 m w.e. (1986 to 95) and 0.58 m w.e. (1996 to 2005), which yields a total average ice thickness reduction of about 10mw.e. The available data from the first three decades indicate strong mass losses as early as the 1940s and 1950s, followed by moderate mass losses until the end of the 1970s. The mass balance data are widely used by the scientific community and represent one backbone of glacier research. Mass balance is recognized as an essential climate variable within the global climate-related observation systems and is, in effect, the largest contributor to the global sea level rise at the turn of the century, apart from thermal expansion of ocean water.

In view of the discrepancy between the relevance of glacier mass balance data and the shortcomings of the available dataset it is strongly recommended to: (1) continue the long-term measurements, (2) resume interrupted long-term data series, (3) when evidence is found of vanishing glaciers, begin as soon as possible with replacement observations, (4) extend the monitoring network to strategically important regions, (5) validate, calibrate and accordingly flag field measurements with geodetic methods, (6) make systematic use of remote sensing and geo-informatics for the assessment of the representativeness of the available data series for their entire mountain range and for the extrapolation to regions without in-situ observations, and (7) make all these data and related meta-information available.

The potential dramatic changes as sketched out for the 21st century by the IPCC report (IPCC, 2007) require critical reflection and a rigorous implementation of the monitoring strategies for glaciers in order to face the challenges of the fast changes in nature and to bridge the gap between historical observation series and the new technologies.

5 The Relevance of Internationally Coordinated Glacier Monitoring

The internationally coordinated glacier monitoring referred to here is a success story: it is among the oldest environmental monitoring networks at international level having built up an unprecedented database which, despite its limitations, remains an irreplaceable treasure of international snow and ice research. Each of its more than 40,000 glacier fluctuation records represents a scientist actively deciding to make his or her data readily available to the scientific community as well as to a vast public. It is, however, not a straightforward task to quantify the success and relevance of this collaborative network operating in a scientific environment. This chapter is an initial effort to discuss and evaluate the relevance of internationally coordinated glacier monitoring in terms of its benefit to a wider scientific collaboration network, and how it can meet the increasing demand for glacier data and information. In addition, current attempts at in capacity-building and public outreach are discussed on the basis of selected examples.

5.1 Benefits of a Scientific Collaboration Network

In order to achieve true advancement in research, there must be unrestricted, free-of-charge sharing of high-quality, long-term and standardized data and information products (ICSU, 2004). However, this stands in direct contradiction to the insistence by the highest bodies in the scientific community, and by the majority of academic journals and funding agencies, on scientific novelty as a prerequisite for acceptance for publication of research papers and proposals. It follows that a successful international monitoring organization needs to be structured in such a way as to address and compensate for this discrepancy.

In the business world a collaboration network is the organizational design best positioned to optimize existing resources and create new value (Shuman & Twombly, 2008): In order to tap the full potential, a well-structured alliance management is required to harness the strengths of all parties that contribute, thereby benefiting and connecting them in new and innovative ways. Translated into the world of glaciology, a professional central monitoring service together with a scientific international collaboration network can consolidate the individual efforts into a joint powerful database and competence system that lead to new and innovative scientific results. As such, an internationally coordinated glacier monitoring increases the visibility of individual undertakings, puts them in an international context, fosters the exchange of knowledge, and facilitates cooperation and access to funding opportunities. In a scientific environment, the establishment of guidelines and standards relating to terminology, data and methods requires the participation of both data producers and data users.

The following is a list of selected measures to increase the benefits of a scientific collaboration network within the GTN-G:

- Continue to strengthen the coordinated efforts and cooperation of the operational bodies (i.e., WGMS, NSDIC, and GLIMS) within the GTN-G, e.g. through:
    - regular (real or virtual) GTN-G *Executive Board Meetings*,
    - joint efforts in promoting glacier monitoring at science conferences and towards national and international agencies, and
    - joint annual reporting in a public format
- Advocate common interests at national and international level, within and outside the glaciological community

- Periodically discuss and re-evaluate the monitoring strategy in order to anticipate early on future developments regarding changes both in glaciers and in monitoring techniques, e.g. through:
    - GTN-G-internal workshops and self-evaluations,
    - interaction with the GTN-G *Advisory Board*, and
    - interaction with the scientific collaboration network
- Facilitate and actively participate in working groups and workshops dedicated to specific issues relevant to
    - the monitoring of glaciers from in-situ and remote-sensing observations, and
    - the corresponding requirements of and opportunities for numerical modeling
- Provide support to members of the scientific collaboration network for joining such workshops, with a special focus on those in developing and threshold countries
- Develop and update guidelines and standards for data, methods, and terminology related to in-situ and remote sensing monitoring of glaciers
- Foster capacity-building and methodological training related to in-situ and remote sensing monitoring of glaciers, e.g. through:
    - summer schools,
    - internships and scientific working stays, and
    - regional sub-networks
- Actively support long-term and/or strategically important monitoring programs, e.g. through:
    - official *Letters of Support*,
    - prominent visibility in official data reports, and
    - methodological and strategic guidance
- Support the extension of the observational network in under-represented regions, e.g. through
    - officially draw attention to the need for new measurement series,
    - on-site support in setting up new observation programs, and
    - methodological and strategic guidance
- Increase the visibility of the scientific collaboration network and of its contributors, e.g. through:
    - easy citation of its data products,
    - joint publication of monitoring results,
    - sessions dedicated to the monitoring of glaciers at international conferences

5.2 Demand for Glacier Data and Information

The present chapter discusses several approaches to estimating the demand for glacier data and information as a measure of the relevance of internationally coordinated glacier monitoring, including a citation index of data reports, key publications, requested glacier data and information, metrics on web-access, and media coverage.

5.2.1 Citation Index of Data Reports

In a scientific environment, an obvious way of estimating the relevance of internationally coordinated glacier monitoring is to analyze the citation index of its data reports and related publications. Most digital libraries, such as *ISI Web of Knowledge*, provide search tools for author, title, abstract, and key words (Hull, Pettifer, & Kell, 2008). These search attributes are, however, not very suitable for finding data reports published by a changing editorial team on behalf of an international organization. A way around this is to use digital libraries that additionally browse the references or even the full text of publications. Table 5.1 shows the search results from *Elsevier's Scirus*, *GoogleScholar* and *GoogleSearch* for titles of WGMS-related data reports. Due to the differing coverage and algorithms of the search engines, a direct comparison of the results is a challenging task (cf. Hull, Pettifer, and Kell 2008; Lewandowski 2010), and an interpretation of derived citation indices, hence, questionable.

Search term	Scirus journal sources	Scirus preferred web	Scirus other web	Google Scholar	Google Search
"world glacier monitoring service"	66	33	1,352	812	39,800
"fluctuations of glaciers"	114	18	416	952	26,400
"fluctuations of glaciers"+ "vol."	71	9	195	501	14,000
"fluctuations of glaciers"+ "world glacier monitoring service"	20	6	192	235	7,720
"glacier mass balance bulletin"	26	5	186	250	5,520
"World glacier inventory"+ "Status 1988"	17	6	47	124	371
"global glacier changes"+ "facts and figures"	5	10	163	62	13,500
"glaciers and the changing earth system: a 2004 snapshot"	18	6	118	142	5,040
"consensus estimates for 1961-2004"	14	4	84	110	384

Table 5.1 Search results from *Scirus*, *GoogleScholar*, and *GoogleSearch* for terms related to the WGMS, its two data report series, and the following specific reports: WGMS (1989), WGMS (2008a), Dyurgerov and Meier (2005), and Kaser et al. (2006). Date of access: 2 March 2011.

In summary, the citation and analysis of derived indices of data reports from the WGMS and its predecessor organizations is challenged by the following issues:

- Data reports extend back to the late 19th century and, thus, into periods not covered by citation databases such as the Web of Science, which began citation in 1945.
- Editors, and publisher changed over time (see Chapter 3.2.2).
- The long series of (changing) acronyms of international organizations (e.g., *ICSU (WDS) – IUGG (IACS) – UNEP – UNESCO – WMO*) is awkward for citing in a paper, especially if several volumes of the data report are to be covered by a reference.
- Using the name of the editor (e.g., Zemp et al.) for the citation of a data report in a paper is even less appreciated by the collaboration network providing the original data as well as by data users.
- Partly as a consequence of the last two points, many data users have been citing the data from the WGMS scientific collaboration network by giving reference to one of the major review papers by data users (e.g., Dyurgerov and Meier 2005).
- For the citation of regional datasets – although the data was requested and received from the WGMS – reference is sometimes given to national data reports or to key publications on the corresponding region by data producers or users.

Over the past years, certain efforts have been made to unify and simplify the data citation issues. In agreement with the auspice organizations and the scientific collaboration network, it is recommended (also to the scientific journals) to cite data received from the WGMS as:

WGMS (YEAR): TITLE. EDITORS. ORGANIZATIONS. Furthermore, the introduction of digital object identifiers (doi) is to be evaluated in order to establish easier and more standardized identification and citation of (evolving) datasets, similar to citation practice four journal articles.

5.2.2 Key Publications Based on WGMS Data

The relevance of internationally coordinated glacier monitoring is reflected in key publications that are based mainly on its globally compiled datasets. This can be done in a qualitative way reviewing the literature for corresponding publications, optionally based on a set of criteria for their importance. Analyzing the citation index of these publications would allow the importance of these studies and, hence, the basic datasets, to be quantified. As an example, the fourth assessment reports of *Working Group I* of the IPCC (2007) is a nalyzed with regard to cited data reports by the WGMS and publications that build on WGMS data. Information on glaciers is covered mainly in Chapter 4 on *Observations: Changes in Snow, Ice and Frozen Ground* (Lemke et al., 2007).

Direct citation of original data reports:

- WGMS(ICSI-IAHS), various years-a: Fluctuations of Glaciers. World Glacier Monitoring Service, Zurich.
- WGMS(ICSI-IAHS), various years-b: Mass Balance Bulletin. World Glacier Monitoring Service, Zurich, http://www.wgms.ch/mbb.html.

Publications which are built mainly on WGMS datasets as the following references show (in original style):

- Cogley, J.G., 2005: Mass and energy balances of glaciers and ice sheets. In: Encyclopedia of Hydrological Sciences [Anderson, M. (ed.)]. John Wiley & Sons, Ltd, Chichester, pp 2555–2573.
- Dyurgerov, M., and J. Dwyer, 2000. The steepening of glacier mass balance gradients with Northern Hemisphere warming. Zeitschrift für Gletscherkunde und Glazialgeologie, 36, 107–118.
- Dyurgerov, M., and M.F. Meier, 2005: Glaciers and the Changing Earth System: A 2004 Snapshot. Occasional Paper 58, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, 118 pp.
- Greene, A.M., 2005: A time constant for hemispheric glacier mass balance. J. Glaciol., 51(174), 353–362.
- Haeberli, W., and C.R. Burn, 2002: Natural hazards in forests: glacier and permafrost effects as related to climate change. In: Environmental Change and Geomorphic Hazards in Forests [Sidle, R.C. (ed.)]. IUFRO Research Series 9, CABI Publishing, Wallingford and New York, pp. 167–202.
- Kaser, G., and H. Osmaston, 2002: Tropical Glaciers. UNESCO International Hydrological Series. Cambridge University Press, Cambridge, UK, 207pp.
- Nesje, A., Ø. Lie, and S.O. Dahl, 2000: Is the North Atlantic Oscillation reflected in Scandinavian glacier mass balance records? J. Quat. Sci., 15(6), 587–601.
- Oerlemans, J., 2005: Extracting a climate signal from 169 glacier records. Science, 308, 675-677.
- Ohmura, A., 2004: Cryosphere during the twentieth century. In: The State of the Planet: Frontiers and Challenges in Geophysics [Sparks, R.S.J. and C.J. Hawkesworth (eds.)]. Geophysical Monograph 150, International Union of Geodesy and Geophysics, Boulder, CO and American Geophysical Union, Washington, DC, pp. 239–257.
- Raper, S.C.B., and R.J. Braithwaite, 2005: The potential for sea level rise: New estimates from glacier and ice cap area and volume distribution. Geophys. Res. Lett., 32, L05502, doi:10.1029/2004GL021981.
- Zemp, M., R. Frauenfelder, W. Haeberli, and M. Hoelzle, 2005: Worldwide glacier mass balance measurements: general trends and first results of the extraordinary year 2003 in Central Europe. In: XIII Glaciological Symposium, Shrinkage of the Glaciosphere: Facts and Analyses, St. Petersburg, Russia [Science, R.A.O. (ed.)]. Data of Glaciological Studies [Materialy glyatsiologicheskikh issledovaniy], Moscow, Russia, pp. 3–12.

Citations of papers by members of the WGMS scientific collaboration network, of which the basic datasets are at least partly available through the WGMS:

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- Clare, G.R., B.B. Fizharris, T.J.H. Chinn, and M.J. Salinger, 2002: Interannual variation in end-of-summer snowlines of the Southern Alps of New Zealand, and relationships with Southern Hemisphere atmospheric circulation and sea surface temperature patterns. Int. J. Climatol., 22, 107–120.
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- Favier, V., P. Wagnon, and P. Ribstein, 2004: Glaciers of the outer and inner tropics: A different behavior but a common response to climatic forcing. Geophys. Res. Lett., 31, L16403, doi:10.1029/2004GL020654.
- Francou, B., et al., 2003: Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16°S. J. Geophys. Res., 108(D5), 4154, doi:10.1029/2002JD002959.
- Francou, B., M. Vuille, V. Favier, and B. Cáceres, 2004: New evidence for an ENSO impact on low-latitude glaciers: Antizana 15, Andes of Ecuador, 0°28'S. J. Geophys. Res., 109, D18106, doi:10.1029/2003JD004484.
- Georges, C., 2004: The 20th century glacier fluctuations in the Cordillera Blanca (Perú). Arctic, Antarctic, and Alpine Res., 36(1), 100–107.
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- Hewitt, K., 2005: The Karakoram anomaly? Glacier expansion and the "elevation effect", Karakoram Himalaya. Mountain Research and Development, 25(4), 332–340.
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- Mölg, T., C. Georges, and G. Kaser, 2003a: The contribution of increased incoming shortwave radiation to the retreat of the Rwenzori Glaciers, East Africa, during the 20th century. Int. J. Climatol., 23, 291–303, doi:10.1002/joc.877.
- Sicart, J.E., P. Wagnon, and P. Ribstein, 2005: Atmospheric controls of the heat balance of Zongo Glacier (16°S, Bolivia). J. Geophys. Res., 110, D12106, doi:10.1029/2004JD005732.

Overall, it is found that from all references dealing with glaciers or ice caps (not including ice shelves, ice sheets and their outlet glaciers) in that chapter, just two directly refer to the original data reports published by the WGMS, but three-quarters of the cited papers are either WGMS data reports, mainly based on WGMS data, or by members of the WGMS scientific collaboration network of which the basic datasets are at least partly available through the WGMS.

5.2.3 Glacier Data and Information Requests

Another measure of relevance is the demand for glacier data and information. According to the ICSU, data and information can be considered as a continuum ranging from raw research data through to published papers (ICSU, 2004). With respect to the relevance of internationally coordinated glacier monitoring, Table 5.2 provides example estimates of requested raw data in digital format, commented information, data reports, and metrics for web access.

	Number of data and information requests		Web statistics		
Year	from users	from journalists	FoG downloads	GMBB downloads	monthly website visits
2008	225	n.a.	1,350	2,500	2,400
2009	225	100	3,050	1,700	3,000
2010	190	30	2,600	4,300	3,800

Table 5.2: Data and information requests for the years 2008, 2009, and 2010. The estimated numbers summarize data and information requests to the WGMS by phone and email

contacts, as well as the monthly visits of the WGMS website and related downloads of *Fluctuations of Glaciers* (FoG Vol. VII, VIII, IX) and of *Glacier Mass Balance Bulletin* (GMBB No. 1−9) in PDF-format. Source: WGMS Annual Reports (unpublished).

In the course of one year, the WGMS staff deals with about 200 data and information requests from various types of users. The latter include, for example, scientists requesting glacier measurements with full meta-data for their research and publications, science officers from non- and governmental agencies looking for commented data series and figures for environmental and climate change reports, or private persons with a special interest in a specific glacier or mountain area. Information requests form journalists range from a few dozen to over 100 a year, usually cumulating after media releases by the WGMS, a glacier publication in a high-ranking academic journal, or following a major glacier (hazard or melt) event. The largest part of the information exchange takes place over the website where details about the WGMS organization, available datasets, and related guidelines are available; as well as latest mass-balance results (from the annual calls) and the regularly published data reports in PDF-format. Over the past few years, the WGMS website has recorded between 1,500 and 4,500 visits per month and annual totals between 4,000 and 7,000 PDF downloads. These numbers vary depending on the methods of analysis and filtering algorithms used (cf. Bertot et al. 1997; Rowbottom, Allam, and Lymer 2005; Tyler and Ledford 2006), but they capture the general tendency and are in good agreement with the overall trends of the metrics of the GLIMS website (Fig. 5.1).

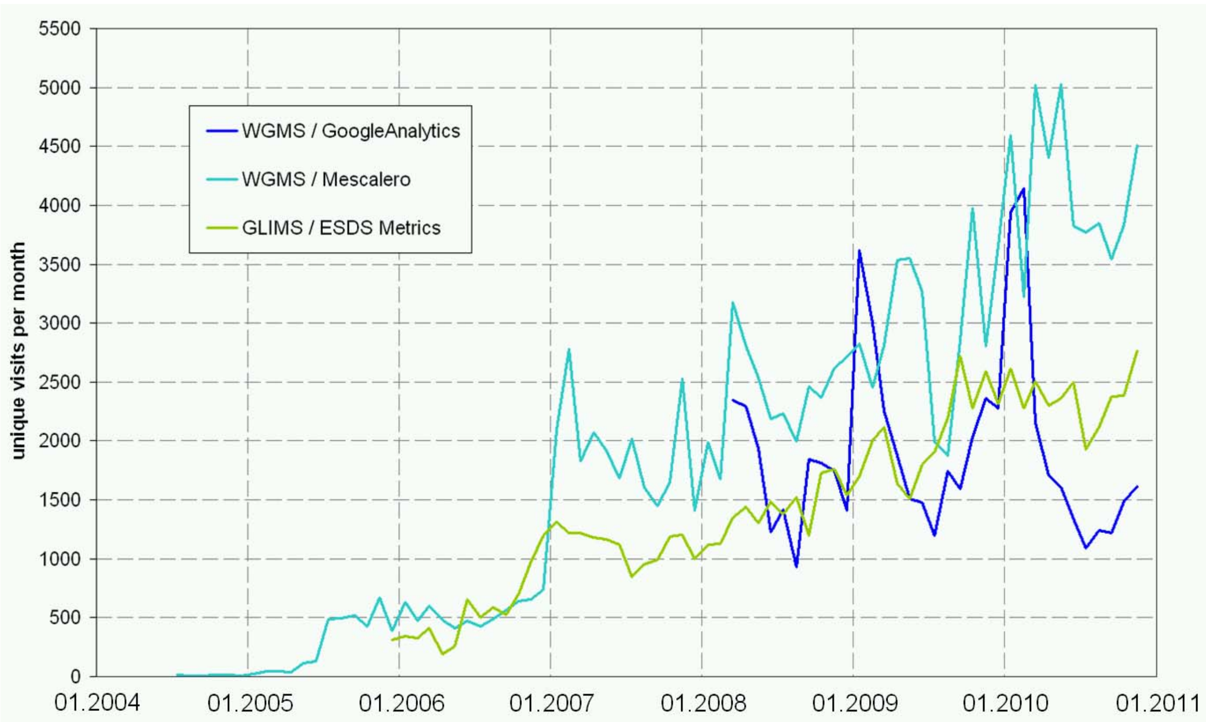

Fig 5.1: Web access metrics for the WGMS and the GLIMS websites. The figure shows the number of single visits per month, using different methods and software packages. As such, the differences between the curves for the WGMS website can be explained to a large extent by different methodologies applied: the tracing approaches by *GoogleAnalytics* and *Mescalero* are cookie and internet-protocol based, respectively, which leads to larger numbers of visits in the latter approach because it includes visits from web crawlers (cf. Rowbottom, Allam, and Lymer 2005; Tyler and Ledford 2006).

5.2.4 Coverage in Print and Online Media

Outside the scientific community, an interesting measure of relevance is the media coverage received by both print and online formats. For the year 2009, the *University of Zurich* analyzed the impact of their press releases with respect to the number of reports taking up the news (Müller 2010). Of the 81 press releases referring to the university and its faculties of science, medicine, economics and arts, glaciers were covered twice in the top ten. The press release by the WGMS about ongoing glacier melt ranked fifth with more than 192 media reports taking up the story. Within Switzerland, the corresponding media coverage ranged from radio reports to news articles in daily newspapers and weekly magazines. All together, the total print runs of newspapers reporting about the press release exceeded one million in Switzerland (Müller, pers. communication based on unpublished *ARGUS* report). By comparison, the press releases within the top four resulted in more than 200 media reports, and the press release from a glacier research project (ranking 10) was taken up by 33 articles. For the same year, a search with *GoogleNews* (search term: "*World Glacier Monitoring Service*", access: 25 March 2011) finds 66 articles worldwide, of which about one third is directly related to the WGMS press release.

5.3 Capacity Building

In a general sense, capacity building can be defined, as adopted by the *Plenary of the UN Conference on Environment and Development* in Rio de Janeiro in 1992, as the ability of a country to follow sustainable development paths, determined to a large extent by its people themselves, its institutions, as well as by its ecological and geographical conditions. Specifically, capacity building encompasses the country's human, scientific, technological, organizational, institutional, and resource capabilities. A fundamental goal of capacity building is to enhance the ability to evaluate and address the crucial questions related to policy choices and modes of implementation among development options, based on an understanding of environmental potentials and limits and of needs as perceived by the people of the country concerned. Also the UNFCCC has long recognized the need for capacity building to assist Parties, especially developing countries, to respond to climate change (UN, 1992).

The GTN-G aims at contributing to capacity building with specific measures related to glacier monitoring, such as hosting trainees and guest scientists, organizing and contributing to workshops, conferences sessions, and training courses dedicated to glacier monitoring, extending travel grants for selected scientists to participate in these events, and providing on-site support for the setup of glacier observation programs. The following are corresponding examples of WGMS contributions to capacity building over the past years:

- Between 2005 and 2010, the WGMS hosted four guest scientists and 13 trainees at its central office.
- Since 2005, WGMS staff member and consultants have provided on-site support for the setup of mass-balance programs in Colombia, New Zealand, and on Greenwich Island, Antarctica. Also, a research project by the *University of Innsbruck*, Austria, reassuming the mass balance measurements at Lewis Glacier, Mount Kenya, was prepared with support of the WGMS.
- The WGMS has repeatedly organized and hosted workshops dedicated to the monitoring of glaciers and ice caps, such as the *General Assemblies of National Correspondents* in 1995 (WGMS, 1998) and in 2010 (WGMS, 2010), the annual GTN-G *Executive Board Meetings* since 2007, or the *ESA User Requirements Meeting* in 2006, which was leading to the *GlobGlacier* project (Paul, Kääb, et al., 2009).

- WGMS staff members regularly contribute to scientific conferences and workshops and represent the glacier monitoring and research communities at meetings with international organizations, such as GCOS, GTOS, IACS, WDS, or with the space agencies. On many occasions, travel grants were organized in order to bring representatives of the WGMS scientific collaboration network to these conferences, workshops, and meetings as well.
- Current efforts are being focused on the establishment of a regular summer school dedicated to the measurement of glacier mass balance.

5.4 Education and Public Outreach

The term *education and public outreach*, also called *science outreach* or simply *public outreach*, is generally defined as an umbrella term for a variety of activities aimed at promoting awareness and understanding of science and making informal contributions to science educations (e.g., Wikipedia 2010). Education and public outreach is certainly an important task for an international monitoring organization acting at the interface between science, politics and the general public. Moreover, glacier changes – the icon of climate change – are an ideal topic in this field for activities ranging from public talks, exhibitions, excursions, and media contributions to the establishment of glacier nature trails. From this range, two activities will be elaborated on and discussed here in more detail.

As the WGMS has long been an integral part of the *Department of Geography*, *University of Zurich*, there exists a long-standing tradition here of bringing the general concepts and latest results of internationally coordinated glacier monitoring to the lecture halls. Since 2009, a new lecture series on the *Monitoring of the Cryopshere in High Mountain Environments* has been taught by staff members of the WGMS. The lecture series is offered in English at the Master level in Geography. Based on UNEP's *Global Outlook on Ice and Snow* (UNEP, 2007), it provides an overview of the different components of the cryosphere and their spatio-temporal scales, and discusses the general concepts, organizations involved, methodologies, and latest results of cryospheric monitoring. One of the main goals is to instruct the students in critical reading and verification of (scientific) news referring to the cryosphere.

During the *International Polar Year* (2007 to 2008), staff members of the WGMS and the Universities of Zurich and Fribourg were invited to consult with the *Swiss Postal Authority* during the production and launch of a special stamp *preserve the glaciers*. The stamp illustrates the retreat of Morteratschgletscher since its LIA maximum extent around 1850 (Fig. 5.2). The stamps were produced using an offset/serigraphy technique and a special ink (optically variable luminescence). Depending on the angle of light, the stamp shows the glacier 150 years ago or as it is today. The release of the special stamp at the beginning of 2009 was accompanied by a joint press release of the WGMS and GCOS Switzerland in the national media and an article (Zemp, Maisch, & Hoelzle, 2009) in the free collector's magazine which appears in English, German, French, and Italian. There was a total print run of 176,000 copies, as well as in PDF-format on the website of the *Swiss Postal Authority*.

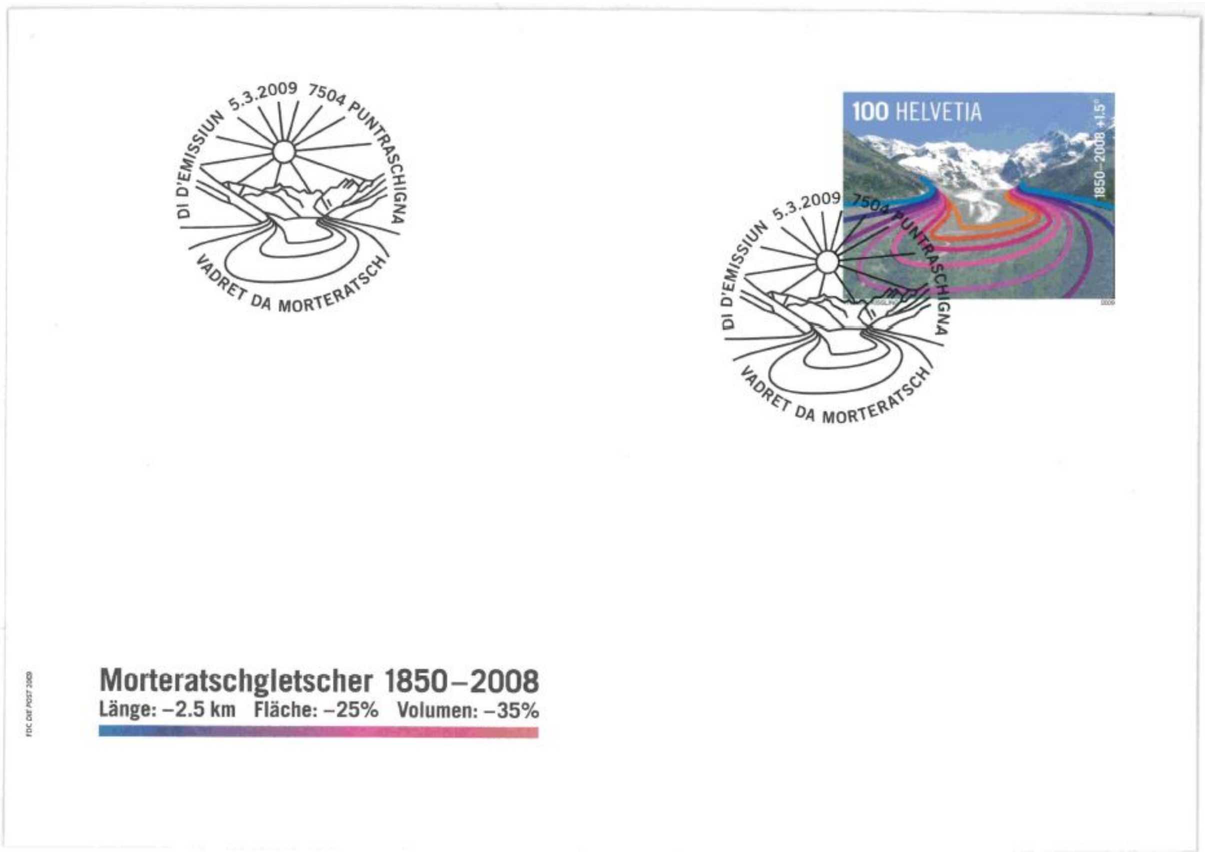

Fig. 5.2: Envelope with special stamp *Vadret Da Morteratsch* and first-day cancellation from 5 March 2009. Source: *Swiss Postal Authority*.

6 General Conclusions and Perspectives

Scientific investigation of the cryosphere enjoys a long tradition and is well developed and funded at national and international levels. Monitoring of the cryospheric components is generally not as well developed, often lacking in operational organizations at the national and international level, and largely without dedicated funding. The monitoring of glaciers and ice caps represents an exception in that it has a long tradition dating back to the late 19th century at international level. It is based on a scientific collaboration network and mostly cross-funded through scientific projects. Only recently, the coordinating office of the WGMS has managed to guarantee its funding for the long-term through the *Swiss GCOS Office* at the *Federal Office of Meteorology and Climatology*, *MeteoSwiss*, and the *Department of Geography*, *University of Zurich*. A major milestone towards the professionalization of the operational monitoring at international level together with strong links to the scientific community has been the setting up of a GTN-G *Steering Committee* to coordinate, support and advice the WGMS, the NSIDC, and the GLIMS initiative for the monitoring of glaciers and ice caps.

The internationally coordinated monitoring efforts for more than a century have resulted in an unprecedented dataset of information about spatial glacier distribution and changes over time. These datasets are readily available to the scientific community and the public, and include reconstructed glacier changes back into the LIA and beyond, direct annual front variation observations back to the late 19th century, six decades of annual and seasonal mass balance measurements, and a preliminary world glacier inventory for the 1970s, mainly based on aerial photographs and maps, with detailed information on more than 100,000 glaciers. This inventory task continues through the present day, now mainly based on satellite images.

The moraines formed towards the end of the LIA, between the 17th and the second half of the 19th century, are prominent features of the landscape, and mark Holocene glacier maximum extents in many mountain ranges around the globe. From these positions, glaciers worldwide have been shrinking significantly, with strong glacier retreats in the 1940s, stable or growing conditions around the 1920s and 1970s, and again increasing rates of ice loss since the mid 1980s. On a time scale of decades, glaciers in various mountain ranges have shown intermittent re-advances. When looking at individual fluctuation series, one finds a high rate of variability and sometimes widely contrasting behavior of neighboring ice bodies. In current IPCC climate change scenarios, the ongoing trend of worldwide and rapid, if not accelerating, glacier shrinkage on the century time scale may lead to the deglaciation of large sectors of many mountain ranges by the end of the 21st century. This will most probably lead to secondary impacts on global sea level rise, regional hydrologic regimes, drastic landscape change in attractive mountain regions, and local hazard situations beyond our historic and Holocene experiences.

Such rapid environmental changes require that the international glacier monitoring efforts make use of the swiftly developing new technologies, such as remote sensing and geo-informatics, and relate them to the more traditional field observations, in order to better face the challenges of the 21st century. In view of this, the last WGMS *General Assembly of National Correspondents* held in Zermatt in 2010 has discussed the main contributions of internationally coordinated glacier monitoring for an improved understanding of glacier processes, distribution and changes, and made the following recommendations:

- continue the long-term observation series of glacier fluctuations,
- re-activate interrupted (long-term) fluctuation series,
- strengthen the monitoring network in under-represented mountain ranges,
- improve the richness and quality of available datasets,
- homogenize, validate, and calibrate long-term fluctuation series,
- initiate the compilation of standardized glacier thickness and volume measurements,
- complete the global detailed glacier inventory, and
- compute and analyze detailed repeat inventories in key regions

To fulfill these tasks, the monitoring strategy has to be regularly assessed with respect to climate-related monitoring of glaciers but also regarding impacts of glacier changes, such as on global sea level rise, on regional hydrological regimes, and on the local hazard situation. This process has to take into account the historical evolution of glacier research and related datasets and also needs to anticipate future developments regarding the changes in both glaciers and monitoring techniques.

For the coming decade the following key tasks are to be tackled within the GTN-G:

- improve the organizational structure and funding situation of glacier monitoring at national and international levels and make use of the scientific collaboration network of the GTN-G and its contacts to international organizations,
- use the GTN-G collaboration network for capacity building,
- develop and improve the monitoring strategy in order to deal with disintegrating and vanishing glaciers,
- enforce the homogenization, validation and calibration of long-term mass balance series,
- initiate (small) scientific workshops focused on specific aspects related to glacier monitoring,
- strengthen the integration of and the cooperation between the glacier in-situ and remote sensing communities,
- foster close contacts with space agencies in order to secure the continuation of space borne missions suitable for glacier monitoring, and
- improve the visibility of regularly updated GTN-G datasets.

A basic requirement for advancing our understanding of causes, effects, and relations to other phenomena of glacier fluctuations is the compilation and free dissemination of global, long-term and standardized data and information. What was already detailed by Forel (1895) in his introductory discourse of *Les Variations Périodiques des Glaciers* is still highly topical more than a century later. However, whereas Forel trusted that increased data compilation and publication would lead to more openness of exchange regarding scientific questions, the internationally coordinated glacier monitoring of the present day has to consider not only the historical evolution of glacier research and related data products, it must also anticipate future changes in glaciers and in monitoring techniques. Still, we shall tackle this challenge with calmness, courage, and dedication.

Acknowledgements

Fifteen years of research he'd filed from one planet alone and they'd cut it to two words: "Mostly harmless." Douglas Adams (1992), about Ford Prefect's trouble with sub-editors.

The writing of this Habilitation was an immense challenge and a great pleasure at the same time – withdrawing from private and professional duties was challenging for a young father and new director of the World Glacier Monitoring Service, but once immersed in the world of glaciers, it was a intensely gratifying to witness this thesis taking shape.

My sincere thanks go to the many great people who supported me during this time! Though it is not possible to list all of them personally here, I will name the most outstanding:

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