CHAPTER 1

Introduction: Global glacier monitoring—a long-term task integrating in situ observations and remote sensing

Michael Zemp, Richard Armstrong, Isabelle Gärtner-Roer, Wilfried Haeberli, Martin Hoelzle, Andreas Kääb, Jeffrey S. Kargel, Siri Jodha S. Khalsa, Gregory J. Leonard, Frank Paul, and Bruce H. Raup

ABSTRACT

This book focuses on the complexities of glaciers as documented via satellite observations. The complexities drive much scientific interest in the subject. The essence—that the world's glaciers and ice caps exhibit overwhelming retreat—is also developed by this book. In this introductory chapter, we aim at providing the reader with background information to better understand the integration of the glacier-mapping initiative known as Global Land Ice Measurements from Space (GLIMS, *http://www.glims.org*) within the framework of internationally coordinated glacier-monitoring activities. The chapter begins with general definitions of perennial ice on land and its global coverage, followed by a section on the relation between glaciers and climate. Brief overviews on the specific history of internationally coordinated glacier monitoring and the global monitoring strategy for glaciers and ice caps are followed by a summary of available data. We introduce the potential and challenges of satellite remote sensing for glacier monitoring in the 21st century and emphasize the importance of integrative change assessments. Lastly, we provide a synopsis of the book structure as well as some concluding remarks on worldwide glacier monitoring.

1.1 WHY THIS BOOK?

The fluctuation of Earth's glaciers—their waxing and waning (e.g., Fig. 1.1)—and glacier ice itself has been a chief source of insight and hard constraints regarding the climate history of Earth and of other planets since the early 1800s (Agassiz 1840, Haeberli 2008; and see the Prologue in the prelims of this book). We have had 50 years of satellite imaging of glaciers starting with the now-declassified observations made by the Corona series. With just over a decade of systematic monitoring by an advanced generation of orbiting multispectral imaging sensors, it is time for a book that documents the advanced methods of analysis of newer data, and the quantitative use of older satellite data as well. This book is finishing about the same time as the USGS super-series of volumes, *Satellite Image Atlas of the Glaciers of the World* (Williams and Ferrigno et al. 2012), which was a mammoth, 30-year undertaking. This book is not an atlas of glacier changes, as a geographically complete or balanced coverage is not its overarching aim. Rather, we examine more completely than ever before the range of measurement methods and products, and the type of knowledge that can be gained from satellite remote sensing, especially from multispectral imaging, of the world's glaciers and ice caps.

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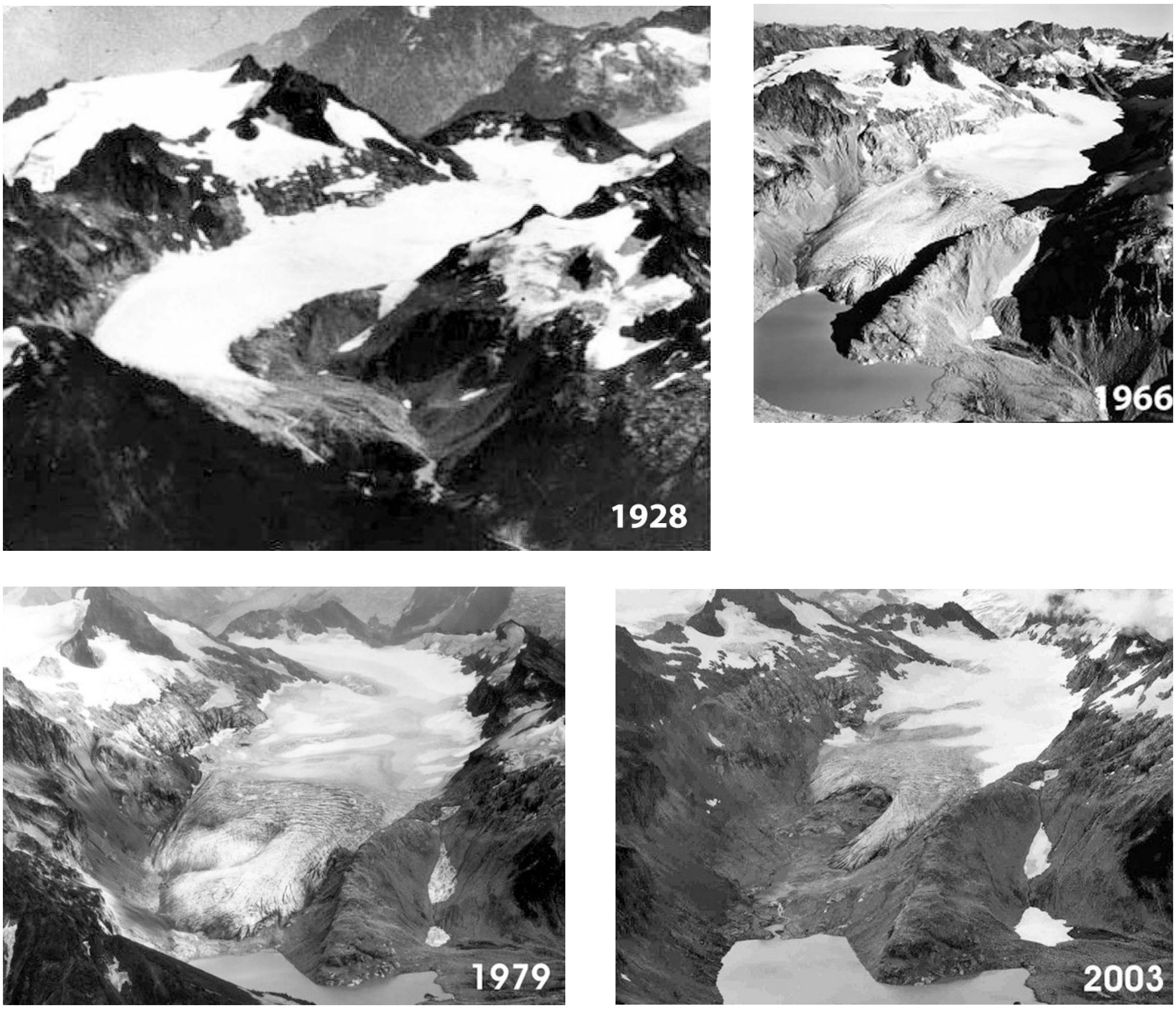

Figure 1.1. Retreat of South Cascade Glacier, U.S.A.: Photographic record of the shrinking South Cascade Glacier in the North Cascade Mountains of Washington, U.S. Note the perennial snow banks at the lower right that are more or less unchanged since 1966 (from *http://ak.water.usgs.gov/glaciology/south_cascade/index.html*).

The subjects of this book are perennial masses of flowing surface ice, as distinguished from other components of the cryosphere, such as snow, river and lake ice, and permafrost. In the next section we define the major categories of flowing ice.

1.2 PERENNIAL SURFACE ICE ON LAND

1.2.1 Definitions

Glaciologists generally differentiate flowing masses of perennial ice into four major types (cf. IPCC 2007, UNEP 2007):

Ice sheet: a mass of land ice, of continental size, thick enough to cover the underlying bedrock topography. Its shape is mainly determined by the dynamics of its outward flow. There are only two ice sheets in the modern world, on Greenland and Antarctica; during glacial periods there were others.

Ice shelf: a thick, floating slab of freshwater ice extending from the coast (originating as land ice). Most present ice shelves, and all of the large ones, are found around Antarctica.

Glacier: a mass of ice on the land surface which flows downhill under gravity and is constrained by internal stress and friction at the base and sides. In general, a glacier is formed and maintained by accumulation of snow at high altitudes, balanced by melting at low altitudes or calving into the sea or lakes.

Ice cap: dome-shaped ice mass with radial flow, usually completely covering surface topography. Much smaller than an ice sheet.

These are the subjects of this book. In some contexts, the noun *glacier* or adjective *glacial* may be used in reference to any of the deforming types of perennial ice, as in the phrase "multispectral glacial analysis," which may refer to analysis of polar ice sheets and ice caps as well as glaciers *senso stricto*. We note that floating ice, whether ice shelves attached to the polar ice sheets or glacier ice floating in lakes or the sea, or icebergs, is no longer "land ice", but it is nonetheless included in this book because of its close association with grounded, true land ice.

In the context of glaciers and ice caps as an essential climate variable, the term "glacier" is used as a synonym for several glacier types, such as ice fields, valley and mountain glaciers, and glacierets. These general definitions are extended here to more specific classifications that serve the requirements of the corresponding applications and should also be understood and referenced in that context. This book uses many technical glaciological terms, which are generally understood by specialists in our field and are not specifically defined here, except as deemed appropriate by the authors. Rather than repeat a glossary of terms, we refer to excellent downloadable glossaries, such as Cogley et al. (2011). For more detailed and fully illustrated descriptions and explanations of terminology, consult *The Encyclopedia of Snow, Ice, and Glaciers* (Singh et al. 2011).

Standards and guidelines for the compilation of an inventory of perennial surface ice on land from aerial photographs, maps, and early satellite images, including such detailed classification schemes, have been defined for the compilation of the World Glacier Inventory (WGI; WGMS 1989) and can be found in UNESCO (1970, 1970/73), Müller et al. (1977), Müller (1978), and Scherler (1983). These standards are also used for in situ glacier fluctuation series (e.g., front variation and mass balance measurements; cf. WGMS Mass Balance Bulletins) and have been revised and updated for satellite-based inventories within the GLIMS project (Rau et al. 2005, Raup and Khalsa 2010).

1.2.2 Global coverage

Perennial surface ice on land presently covers some 10% (or 1.6×10^6 km^2) of the Earth's land surface; coverage during the ice age maxima attained up to about three times this amount (Paterson 1994, Benn and Evans 1998). An overview of area, volume, and sea level equivalent of ice sheets, ice shelves, glaciers, and ice caps is given in Table 1.1, based on IPCC (2007). Glaciers and ice caps, excluding those adjacent to the ice sheets of Greenland and Antarctica, cover an estimated area between 500 and 550×10^3 km^2 (e.g., 510×10^3 km^2 by Ohmura 2004; 518×10^3 km^2 by Radić and Hock 2011, or 540×10^3 km^2 by Dyurgerov and Meier 2005). These estimates are based mainly on the WGI (WGMS 1989). If all surface land ice melted away, sea level would rise by about 64 m, with the Antarctic Ice Sheet contributing 57 m, the Greenland Ice Sheet about 7 m and all other glaciers and ice caps a few decimeters.

There are fundamental differences in the processes (and their timescales) driving the changing properties of perennial surface ice on land. Due to the large volumes and areas, the two continental ice sheets actively influence global weather and climate over timescales of days to millennia, whereas their dynamical responses (such as flow speeds) to climate changes tend to occur quite sluggishly—on timescales of decades to millennia, according to our current understanding. Glaciers and small ice caps, with their much smaller volumes and areas, react much faster to climatic effects (i.e.,

Table 1.1. Area, volume, and sea level equivalent of perennial surface ice on land components (from IPCC 2007).

Cryospheric component	*Area* (10^6 km^2)	*Volume* (10^6 km^3)	*Potential sea level rise* (m)
Ice sheets	14.0	27.6	63.7
Ice shelves	1.5	0.7	~0
Glaciers and ice caps	0.51–0.54	0.05–0.13	0.15–0.37

Data for the ice sheet in Greenland come from Bamber et al. (2001); the numbers for the ice sheet in Antarctica and the ice shelves are published by Lythe et al. (2001). The minimum and maximum estimates for glaciers and ice caps are from Ohmura (2004) and Dyurgerov and Meier (2005), respectively, which are both mainly based on the WGI (WGMS 1989), excluding glaciers and ice caps surrounding Greenland and Antarctica.

timescales range between months and centuries); though the smaller ice masses influence local climate, their influence on global climate is minor. The smaller ice masses are good indicators of climate change on the human timescales of modern concern, and they influence ecosystems and human activities on a local to regional scale. As the focus of this book is on glaciers and ice caps, and less on the polar ice sheets, our introduction concentrates on these two components of land ice. We use the term "glacier" in this book to represent both alpine glaciers and ice caps, since the same measurement principles are applicable. Good overviews on the state of the art concerning the monitoring of ice sheets and ice shelves can be found in Bentley et al. (2007) and in IPCC (2007).

1.3 GLACIERS AND CLIMATE

1.3.1 Formation of glaciers and their dynamical controls

Glaciers form where snow deposited during the cold or humid season does not entirely melt during the warm or dry portions of the year. This seasonal snow gradually densifies under the weight of the overlying layers and transforms into perennial firn and finally, after the interconnecting air passages between the grains are closed off, into ice (Paterson 1994). The ice from such accumulation areas then flows under the influence of gravity down to lower elevations, where it melts and sublimates in ablation areas. Accumulation and ablation areas are separated by the equilibrium line, where the balance between gain and loss in ice mass in a given season is exactly zero. The so-called equilibrium line is of course not really a line, but rather a meandering and highly dynamic feature which is normally approximated as a single elevation (equilibrium line altitude, ELA) for a given year. The spatial distribution of glaciers is thus primarily a function of climate, including mean annual air temperature and annual precipitation (Fig. 1.2), modified by the terrain which influences (1) the amount of incoming direct solar radiation and indirect radiation reflected by or emitted from nearby terrain or blocked in shadow areas; (2) microclimate; (3) the flow of ice from higher elevations to lower elevations; (4) the supply of rock debris; and (5) the accumulation of snow due to indirect sources such as avalanches and wind-blown snow. Other locally important controls on glaciers, which may vary locally, include deposition of albedo-lowering aerosols and dust, as well as suspended atmospheric aerosols, which can affect atmospheric lapse rates. These many variables can result in different dynamical behavior of adjacent glaciers and contribute to a wide variation in regional and global behavior of glaciers.

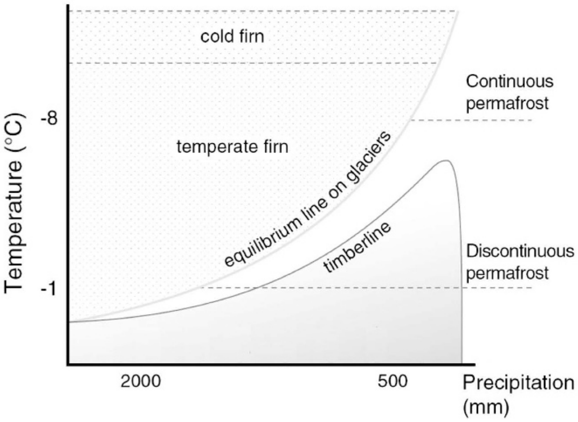

Figure 1.2. Schematic diagram of glacier, permafrost, and forest limits as a function of mean annual air temperature and average annual precipitation. Forests verge on glaciers in humid maritime climates and grow above permafrost in dry continental areas (based on Shumskii 1964 and Haeberli and Burn 2002).

In humid maritime regions, with relatively high precipitation and temperature, and long melting seasons, the equilibrium line occurs at relatively low altitude because of the large amount of ablation required to eliminate thick snow layers (Shumskii 1964, Haeberli and Burn 2002). "Temperate" glaciers with firn and ice at melting temperature dominate these landscapes. Such ice bodies typically exhibit relatively rapid flow, high mass turnover (where mass turnover may be defined as the sum of the absolute values of ablation and accumulation), and react strongly to atmospheric warming by enhanced melt and runoff. The glaciers and ice caps of Patagonia and Iceland, the western Cordillera of North America and in the mountains of New Zealand and Norway are of this type. The lower parts of temperate glaciers may extend into forested valleys, where summer warmth and winter snow accumulation prevent development of permafrost. In contrast, under dry continental conditions, with low precipitation and temperature, and short melting seasons, such as in northern Alaska, arctic Canada, subarctic Russia, parts of the Andes near the Atacama desert, and in many central Asian mountain chains, the equilibrium line is usually found at relatively high elevation. In these regions, glaciers lying far above the tree line can contain—or entirely consist of—cold firn/ice well below melting temperature, have low mass turnover, and are often surrounded by permafrost (Shumskii 1964).

1.3.2 Glacier reactions to climate change, and response times

The reaction of a glacier to a change in climate involves a complex chain of processes (Nye 1960, Meier 1984). Atmospheric conditions (solar radiation, air temperature, precipitation, wind, cloudiness, etc.) influence the mass and energy balance at the glacier surface (cf. Kuhn 1981, Oerlemans 2001). Air temperature plays a dominant role as it is related to the radiation balance, turbulent heat exchange, and controls solid versus liquid precipitation. Over periods of years to 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 finally leads to changes in glacier length, the advance or retreat of glacier tongues, and thickening or thinning of ice. In short, the glacier mass balance at a point is the direct and undelayed signal of annual atmospheric conditions, whereas the advance or retreat of glacier tongues (i.e., the "horizontal" length change or the glacier area) constitutes an indirect, delayed, integrated, and easily observed, filtered signal of climatic change (Haeberli 1998). Glacier attributes such as slope and hypsometry (distribution of ice area or mass with elevation) affect the response time through their influence on flow speeds and volume of ice responding at different elevations (Raper and Braithwaite 2009). Total glacier mass divided by total annual accumulation (above the equilibrium line) has the units of time and is a reasonable characteristic response time that can be assigned to any glacier. Variability in response times (however defined) is a source of variability in observed glacier responses to climate change in space and time; heterogeneity in regional climate change is another major cause.

The complexities of the dynamic response become less important if the time interval considered is sufficiently long (i.e., longer than it takes a glacier to complete its adjustment to a specific climatic change—Jóhannesson et al. 1989, Haeberli and Hoelzle 1995, Raper and Braithwaite 2009). Over such extended time periods—several decades for most smaller glaciers—cumulative length and mass change can be directly compared (Hoelzle et al. 2003). Exceptions to these rules include: heavily debris-covered glaciers, which have reduced melting and retreat and thinning rates; glaciers terminating in deep water bodies, which cause enhanced melting and calving; and glaciers periodically undergoing mechanical instability and rapid advance ("surges" or similar) after extended periods of stagnation and recovery. Glaciers that are not influenced by such conditions are widely recognized to be among the best climate change indicators (IPCC 2001, 2007, GCOS 2004, 2006). They convert small changes in climate into a pronounced length and thickness change. Length fluctuations—even more so than area and volume—are easily understood by the general public as caused by climate change (Fig. 1.1); spatiotemporal (heterogeneous) variability in length responses, though, is harder for the public to understand and remains a key area where scientists must communicate complexity—in simple, comprehensible terms—to the public. Large glaciers, and small ones in polar climates, have such low mass turnover relative to total glacier mass that they take a very long time to respond to climate change; hence, they are still responding to climate conditions integrated over periods extending well before the increase of greenhouse gases, but increasingly these glaciers are starting to respond to the more recent changes. We refer readers to this book's Chapter 33 (Kargel et al.) for further explanations, illustrations, and implications of glacier response times and reaction times.

1.3.3 Reporting glacier change rates

The length, area, thickness, and volume or mass of glaciers are fundamental measurable parameters. Glaciers' dimensional changes may be compared in absolute terms (m/yr, m^2/yr, and m^3/yr, for example), but such comparisons are strongly dependent on glacier size and are not very useful in comparing dynamical conditions.

A more meaningful approach to comparing glaciers' dynamical states is to report area change rates in relative terms (i.e., percentage change in area per unit time). But surprisingly unstated in the glaciology community is the precise meaning of percent per annum (%/yr) change. Two approaches are used in this book, including simple division and compound interest formulations, described below. Neither method is a correct model for all glaciers generally, but for small percentages of cumulative change over the reporting period they both converge to the same values, and they each offer a way to compare retreat or growth rates. In the regional chapters of this book, both reporting methods are used, according to author preference as well as the nature of glacier retreat (or in some cases, growth) in those regions.

One method—most commonly used in the literature—is a division of the percentage change in the area of a glacier by the number of years between two observations of area to get a number with units %/yr. For example, 50% loss over 10 years would be reported as an area loss of 5%/yr, where the 5% is relative to the area present at the start of the period. However, this approach does poorly for large total percentage changes; consider, for example, that percentage shrinkage rates reported for the same glacier, hypothetically shrinking at a constant rate of area loss, will yield different shrinkage %/yr for different time periods, because the initial area at each time period differs. A further implication is that the retreat rate of the margins drastically increases as shrinkage progresses; glaciers generally do not retreat that way.

An alternative way to annualize changes that are measured over multiple years is to use the compound interest formula. Use of this formula implies that the glacier annually loses the same percent of each year's updated area. The compound interest case implies deceleration of area lost per year. This slowing can have a physical interpretation, such as reduced perimeter or retreat into higher elevations and into shadowed niches, but it also implies that the glacier can never disappear.

1.4 INTERNATIONAL GLACIER MONITORING

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 (see the Prologue in the prelims of this book). The discovery and early characterization of ice ages in the 19th century, and their connection to modern glaciation significantly contributed to the understanding of the evolutionary development of the Earth; they 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 provide insight into processes of the formation of the ice ages (Agassiz 1840). Since then, the goals of international glacier monitoring have evolved and multiplied (Haeberli 2004). The origin and development of the GLIMS initiative, including its international organization and structure, was summarized in the Preface. The international scope of GLIMS—including core institutions, regional centers, steward institutions, and others who are affiliated indirectly through authorship in this book—is further indicated in Fig. 1.3. The fact is, the task to assess the state and dynamics of the world's glaciers is an immense undertaking and is internationally recognized as important. Today, glaciers are recognized as key indicators of global climate change and as important contributors to global sea level rise, regional water cycle, and local alpine hazards.

1.4.1 History of international glacier monitoring in the 19th and 20th centuries

Worldwide collection of information about ongoing glacier changes was initiated in 1894 with the foundation of the International Glacier Commission at the Sixth International Geological Congress in Zurich, Switzerland. In the beginning, internationally coordinated glacier monitoring focused mainly on glacier fluctuations, beginning with collection and publication of front variation data and, after the late 1940s, expanding to include glacier mass balance series (Haeberli 2007). Today, satellite image analysis requires validation by ground-based studies as well as a longer baseline of observations provided by the long-term monitoring of "benchmark glaciers". The validity and understanding of satellite-based analysis depends on the systematic acquisition of a rich variety of glaciological parameters for benchmark glaciers. Needed as well is archival of historic map and photographic evidence of glacier behavior in the decades preceding the advent of satellite imaging and continuing still (e.g., image coverage of South Cascade Glacier, Fig. 1.1). Some European glaciers have accurate terminus position data going back to the mid-19th century.

Summaries of references to historical reports are given in Hoelzle et al. (2003) and WGMS (2008). In the 1970s a world glacier inventory had been planned, resulting in the compilation of detailed and preliminary regional inventories that form a statistical basis for the geography of the world's glaciers (WGI; WGMS 1989). In 1986 the World Glacier Monitoring Service (WGMS; *http://*

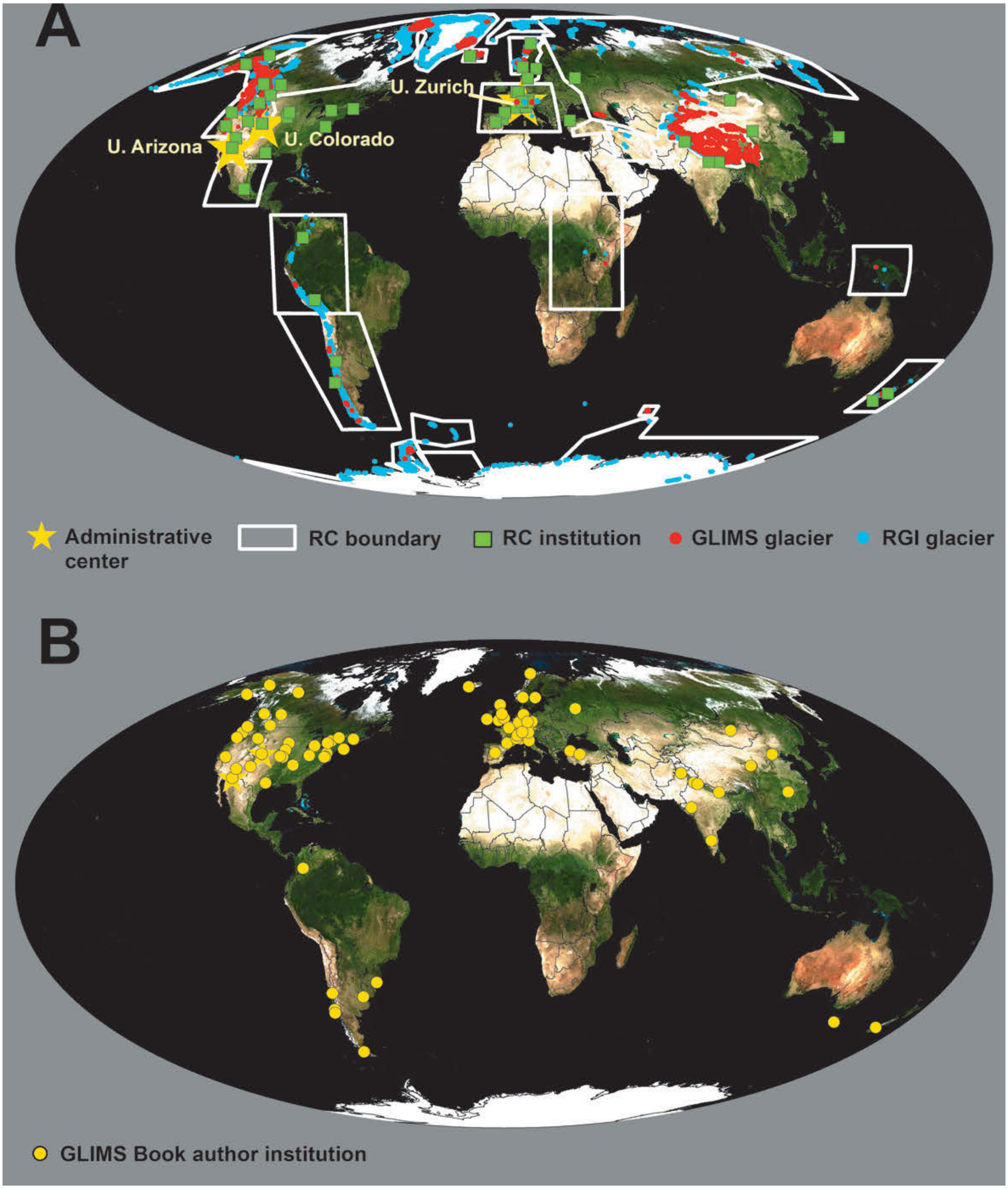

Figure 1.3. (A) Global distribution of the institutions affiliated with GLIMS (RC = Regional Center; RGI = Randolph Glacier Inventory); and (B) global distribution of authors associated with this book. Figure also available as high-resolution Online Supplement 1.1.

www.wgms.ch) took on the maintenance and continuation of the collection of standardized information about ongoing glacier changes, when the two former ICSI (International Commission on Snow and Ice) services, the PSFG (Permanent Service on the Fluctuations of Glaciers) and TTS/WGI (Temporal Technical Secretary for the World Glacier Inventory) were combined (Haeberli 2007). Today the WGMS is a service of the International Association of the Cryospheric Sciences (IACS) within the International Union of Geodesy and Geophysics (IUGG) and of the International Council for Science (ICSU). It maintains a network of local investigators and national correspondents in all the countries involved in glacier monitoring.

1.4.2 The Global Terrestrial Network for Glaciers (GTN-G)

In close collaboration with the National Snow and Ice Data Center in Boulder, Colorado (NSIDC) as well as with the GLIMS initiative, the WGMS has been in charge of the Global Terrestrial Network for Glaciers (GTN-G) within the Global Climate/Terrestrial Observing System (GCOS/GTOS, cf. Haeberli et al. 2000, Haeberli 2004) since its creation in 1998 (Haeberli et al. 2000). A recently established GTN-G Steering Committee coordinates, supports, and advises the three operational bodies (i.e., WGMS, NSIDC, GLIMS) concerning the monitoring of glaciers. This Steering Committee consists of an Executive Board that is responsible for the development and the implementation of the monitoring strategy as well as for the coordination of the operational work, and an Advisory Board under the lead of the IACS/IUGG that is tasked to support, consult, and periodically evaluate the work of the Executive Board and its three bodies.

GTN-G aims at combining (a) in situ observations with remotely sensed data, (b) glacier process understanding with global coverage, and (c) traditional measurements with new technologies by using an integrated and multilevel strategy (Haeberli 1998, 2004). With this strategy, GTN-G is designed to provide quantitative, comprehensive, and easily understood information in connection with questions about process understanding, change detection, model validation, and environmental impacts. The intended audience includes the scientific community, 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 geoinformatics. The GTN-G multilevel monitoring strategy following GHOST includes the following main components or "tiers":

Tier 1: Multicomponent system observation across environmental gradients. This first level stresses the importance of establishing a multicomponent glacier observation system across environmental gradients with primary emphasis on spatial diversity at large (continental) scales or along elevation belts of high-mountain areas. Special attention is given to long-term measurements. These are to be complemented by new observation series in order to cover large-scale transects such as the American Cordilleras or a profile from the Pyrenees through the Alps and Scandinavia to Svalbard.

Tier 2: Extensive glacier mass balance and flow studies within major climatic zones for improved process understanding and calibration of numerical models. Full parameterization of coupled numerical energy, mass balance, and flow models is based on detailed observations for improved process understanding, sensitivity experiments, and extrapolation to regions having less comprehensive measurements. Ideally, sites are located near the center of the range of environmental conditions of the zone that they are representing. The actual locations will depend more on existing infrastructure and logistical feasibility than on strict spatial guidelines, but there is a need to capture a broad range of climatic zones (such as tropical, subtropical, monsoon-type, mid-latitude maritime/continental, subpolar, and polar).

Tier 3: Determination of regional glacier volume change within major mountain systems using low-cost methods. There are numerous sites that reflect regional patterns of glacier mass change within major mountain systems, but they are not optimally distributed. Observations with a limited number of strategically selected index stakes (annual time resolution) combined with precision mapping at about decadal intervals (volume change of entire glaciers) for smaller ice bodies, or with laser altimetry or kinematic GPS for large glaciers constitute optimal data compilations that contribute towards analytical extrapolation into remote areas of difficult access. Repeated mapping alone provide important data at a lower time resolution (decades).

Tier 4: Long-term observations of glacier length change within major mountain ranges for assessing the representativeness of mass balance and volume change measurements. At this level, spatial representativeness is the highest priority. Locations are optimally based on statistical considerations concerning climate characteristics, size effects, and dynamics (calving, surge, debris cover, etc.). Long-term observations of glacier length change at a minimum of about 10 sites within each of the important mountain ranges should be measured either in situ or with remote-sensing techniques at annual to multiannual frequencies.

Tier 5: Glacier inventories repeated at time intervals of a few decades through satellite remote sensing. Continuous updating of preliminary inventories and repetition of detailed inventories using aerial photography or satellite imagery should make it possible to attain global coverage and to serve as validation of climate models. The use of digital terrain information in geographic information systems (GISs) greatly facilitates automated procedures of image analysis, data processing, and modeling and interpretation of newly available information. Preparation of data products from satellite measurements must be based on a long-term program of data acquisition, archiving, product generation, and quality control.

Tiers 2 and 4 mainly represent traditional methodologies, which remain fundamentally important for deeper understanding of the involved processes, as training components in environment-related educational programs and as unique demonstration objects for the public. Tiers 3 and 5 represent opportunities for the application of new technologies.

Detailed information on GTN-G and GHOST can be found in Haeberli et al. (2000) and Haeberli (2004) with updates on the present state in several GTOS reports (Haeberli and Barry 2006, Zemp et al. 2008, 2009).

1.4.3 Available datasets

The WGMS hosts an unprecedented collection of information about spatial glacier distribution and changes over time that is readily available to the scientific community and the public. At present, the database contains glacier front variations and mass balance observations. The available length change and mass balance observations are both strongly biased towards the Northern Hemisphere and Europe (Fig. 1.4). The WGI is mainly based on aerial photographs and maps and includes detailed information on location, classification, area, length, orientation, and altitude range.

GLIMS was established in 1999 to continue the inventory task with spaceborne sensors (cf. Kieffer et al. 2000, Bishop et al. 2004, Kargel et al. 2005) in close cooperation with the National Snow and Ice Data Center (NSIDC; *http://www.nsidc.org*) and the WGMS. A geographic database and Web interface were designed and implemented at NSIDC to host and distribute both the data from the World Glacier Inventory (glacier label points with attribute tables) and the new GLIMS data (glacier outlines with attribute tables) (Raup et al. 2007a, b). In addition to the WGI data, the GLIMS database as of press time (early 2014) contains 122,414 digital outlines and other data for 117,201 glaciers totaling 420,859 km^2 (latest snapshot only); in addition, 3,403 glaciers have multitemporal outlines (Fig. 1.5). Complementary projects, such as the International Polar Year (IPY) by both NASA and ESA and GlobGlacier by the European Space Agency (cf. Paul et al. 2009), have aimed at making major contributions to the current WGMS and GLIMS databases. Most recently, a program to augment and fill in the gaps of the GLIMS inventory for the purpose of sea level predictions for the next IPCC Assessment Report was undertaken in the development of the Randolph Glacier inventories (up to version 3 at press time).

Within GTN-G, consistency and interoperability of the different glacier databases is a goal of current work. A map-based Web interface is currently under implementation (*http://www.gtn-g.org*). This new one-stop portal is being developed to spatially link the different datasets and to provide users with a fast overview of all available data and corresponding metainformation. It will also offer guidance for data submission and requests in digital and standardized formats. The GLIMS database viewer also gives access to various glacier data sets, such as the WGI.

1.4.4 Challenges of the 21st century

Glaciers around the globe have been shrinking dramatically since their Holocene maximum extent towards the end of the Little Ice Age, between the 17th and the second half of the 19th century, with increasing rates of ice loss since the mid-1980s (Zemp et al. 2007a, WGMS 2008). Under the present climate scenarios (cf. IPCC 2007), the ongoing rapid and perhaps accelerating trend of worldwide glacier shrinkage, on the century timescale, is most likely of nonperiodic nature. International monitoring strategies, hence, have to consider extreme perspectives such as the deglaciation of large parts of many mountain ranges within the coming decades (e.g., Zemp et al. 2006, Nesje et al. 2007). In that context, international glacier monitoring faces major challenges, such as the following:

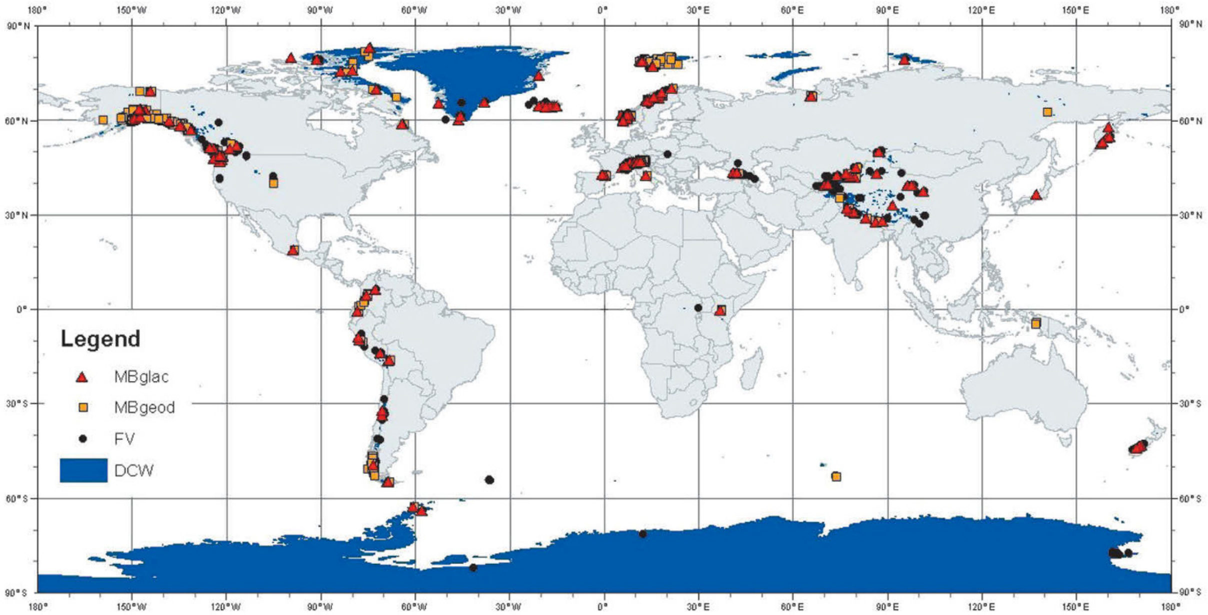

Figure 1.4. Worldwide glacier monitoring. The global distribution of ice on the land surface (blue) is shown with locations of glacier front variation (black circles) and mass balance measurements (red triangles: direct glaciologic; yellow squares: geodetic). Data sources: locations of glacier observations provided by the WGMS, Zurich, Switzerland; background glacier cover is based on the glacier layer of the Digital Chart of the World, provided by the NSIDC, Boulder, U.S.A. Figure also available as Online Supplement 1.2.

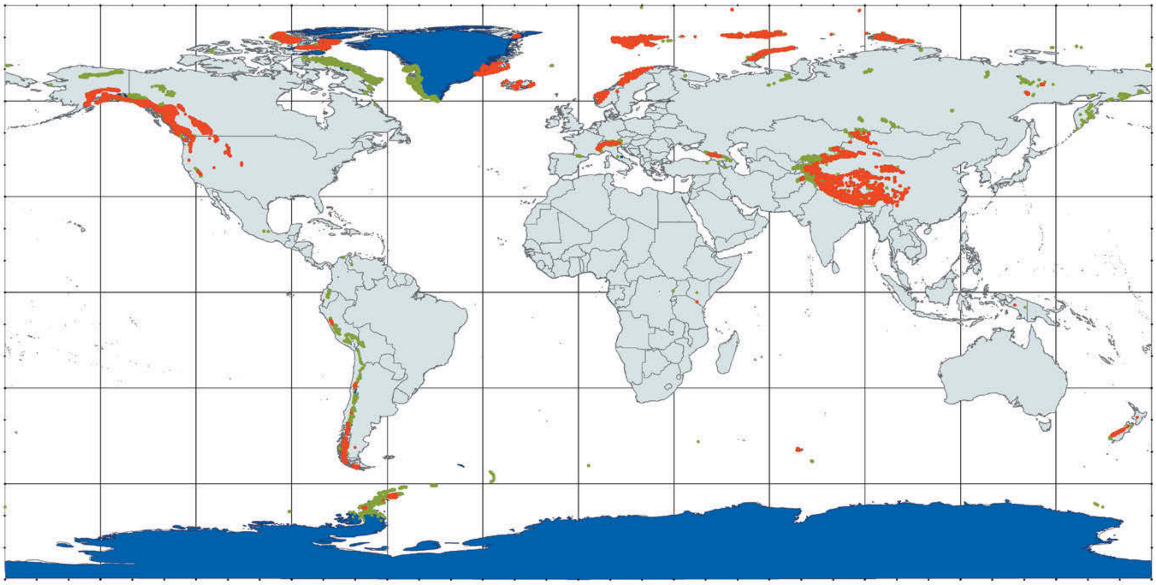

Figure 1.5. Global distribution of inventoried glaciers. The global distribution of surface land ice (blue) is overlain with the location of glaciers with available digital outlines collected within the GLIMS initiative (red) and the locations of the point coordinates of glaciers with detailed information of the WGI (WGMS green). Data sources: WGI data provided by the WGMS, Zurich, Switzerland; glacier layers of GLIMS data and of the Digital Chart of the World provided by NSIDC/GLIMS, Boulder, U.S.A. GLIMS Inventory date: January 2014. Figure also available as high-resolution Online Supplement 1.3.

- The dramatic changes leading to the complete vanishing of some glaciers within the front variation and mass balance monitoring network.
- The downwasting of many glaciers, rather than their dynamic retreat, over the past two decades that has decoupled glacier horizontal extent (i.e., length, area) from current climate, so that glacier length and area changes have become a climate proxy for nonlinear behavior.
- The current high rates of ice loss demanding a repetition rate of glacier inventory activities of less than a few decades.
- Regional pilot studies (e.g., from the European Alps) showing that detailed change assessments based on inventories of different time periods and sources (e.g., 1850s based on historical maps and moraine dating, 1970s based on aerial photographs and maps, and 2000 based on satellite images) are laborious and often hampered by problems with firn–ice differentiation as well as with disintegration and vanishing of glaciers between the times analyzed.
- The limited capacities of traditional glacier-monitoring systems of the 19th and 20th century, which are mainly based on research institutions and funded through time-limited research projects.
- The growing resources needed to manage the exponentially increasing data volume from remote-sensing analysis and the corresponding metadata and data quality information.
- The bias of the present monitoring network toward observations in the Northern Hemisphere.
- The interruption of long-term glacier observation series due to financial, political, and other reasons.

To keep track of fast environmental changes and to assess corresponding impacts on landscape evolution, freshwater supply and natural hazards, international glacier-monitoring efforts will have to make use of the rapidly developing new technologies (remote sensing and geoinformatics) and relate them to the more traditional methods. In order to face such challenges of historical dimension, it is fundamental that glacier monitoring of the 21st century:

- Completes a detailed global glacier inventory from early in the period of anthropogenic global warming to serve as a baseline (e.g., for the 1970s—cf. WGMS 1989).
- Extends the inventorying effort to another complete inventory during the early 21st century satellite observation era.
- Continues long-term fluctuation series (i.e., front variation and mass balance) in combination with satellite-based decadal determinations of volume/thickness, and length changes from geodetic methods in order to verify annual in situ observations.
- Reinitiates interrupted field monitoring to provide long-term series in strategically important regions and strengthens the current monitoring network in the Tropics and the Southern Hemisphere.
- Integrates reconstructed glacier states and variations into the present monitoring system in order to extend the historical set of front variation data and to place the measured glacier fluctuations of the last 150 years into context with glacier variations during the Holocene.
- Concentrates the extension of the in situ observation network mainly on (seasonal) mass balance measurements, because they are the direct glacier signal to atmospheric conditions.
- Adds to the present long-term monitoring series of benchmark glaciers (many of which are soon to vanish) with parallel observations on larger or higher elevation glaciers (a new benchmark program).
- Makes use of decadal-scale digital elevation model differencing, and similar techniques, to extend and understand the representativeness of in-situ mass balance measurements for regional ice volume changes.
- Defines key regions where the glacier cover is relevant for climate change, sea level rise, water resources, and natural hazards, in which glacier changes since the end of the Little Ice Age, until the beginning of the 21st century and the coming decades are inventoried on a detailed level.
- Periodically reevaluates the feasibility and relevance of the monitoring strategy and its implementation.

Glacier monitoring has to overcome national boundaries in order to coordinate observations over entire mountain ranges. Glacier observation data are to be provided, via the corresponding data centers, to the scientific community and wider public according to international standards and strategies. This requires recognition of the importance of monitoring activities, data standards, and metadata by the sponsoring agencies and the research institutions. For this purpose the organizational structure and cooperation of the services involved in international glacier monitoring (i.e., WGMS, NSIDC, and GLIMS) shall be further strengthened within GTN-G. The central monitoring services should be coordinated by an international cooperation structure with links to scientific umbrella organizations, have an adequate financial basis, and work to strengthen their network to data providers, data users, national agencies, and international organizations.

1.5 GLACIER OBSERVATIONS FROM SPACE

Glaciers were one focus of satellite observations from the beginning of the Landsat mission (1972). Although the large regions covered by satellite data were mentioned in most studies as a strong benefit for glacier-related applications, mapping of glacier extent was introduced quite late. Early applications focused on the mapping of snowlines (Østrem 1975, Rott 1976) or the analysis of glacier movement and flow (Krimmel and Meier 1975), at that time using contrast-enhanced photographic prints rather than digital data. The full potential of working directly with the digital data was delayed until appropriate computer technology became available. The utility of these data for glacier mapping was advanced by Rundquist et al. (1980) and Howarth and Ommanney (1986) when they proposed to use Landsat data for creating glacier inventories.

With the availability of higher spatial resolution (30 m) data in six spectral bands from the Thematic Mapper (TM) sensor in 1984, an important step forward was achieved for spaceborne glacier monitoring. This instrument demonstrated that snow and ice were spectrally distinguishable from clouds, and automated glacier mapping at a global scale became feasible. In the following years, a large number of studies used TM data for glaciological applications (e.g., mapping of outlines and terminus changes, snow and ice zones, flow velocities). With the advent of the Terra ASTER and Landsat ETM+ sensors, glaciers were one of the major targets from the beginning (Bindschadler and Scambos 1991, Kieffer et al. 2000, Raup et al. 2000) and simple but robust techniques were developed to map (debris-free) glaciers automatically (Albert 2002, Paul 2002). In combination with geographic information systems (GISs) and DEM fusion, the automated extraction of detailed glacier inventory data for all glaciers in a satellite scene became feasible (Kääb et al. 2002, Paul et al. 2002).

In parallel, microwave sensors were also increasingly being used for glaciological studies, in particular for multitemporal observations of the firn line, to derive glacier velocity and elevation changes from interferometric techniques, or to measure changing terminus positions of tidewater glaciers (cf. Bamber 2006). In contrast to optical sensors, clouds are transparent to microwaves, allowing for the study of glaciers independent of cloud conditions and solar illumination, and thus on a more frequent basis. Due to the similarity of microwave backscatter from snow and ice with other surrounding material, mapping of glacier extent from microwave sensors has only rarely been tested (e.g., Hall et al. 2000). Hence, the specific glaciological applications of microwave sensors are different from those of optical sensors.

1.5.1 Satellite observations in GTN-G

As described above (Section 1.4.2), the frequent update of glacier inventories from satellite data at time intervals of a few decades is implemented as Tier 5 in the GTN-G (e.g., Haeberli 2006). In this regard, Landsat TM/ETM+ data are particularly useful for this task due to the large area covered in a single image and the free availability of the scenes stored in the USGS archive (USGS 2008). To date, two major tasks can be identified for glacier monitoring from satellite data (GCOS 2006): (1) creating a digital two-dimensional (2D) baseline glacier inventory and (2) change assessment from repeat coverage. This is also related to the two main deficits of the former World Glacier Inventory (WGI) from the 1970s (WGMS 1989): The detailed inventory information in the WGI is not complete and the data are stored as point information. While the incompleteness causes large uncertainties for prediction of future sea level rise (e.g., Raper and Braithwaite 2006, Rahmstorf 2007), the lack of mapped outlines means that change assessment is nearly impossible. Moreover, in most countries about 30 years have passed since the last inventory work was done, and the time for an update has come. It is a specific aim of the GLIMS initiative to overcome these issues by deriving the required glacier information from satellite data in yet uncovered regions and supplement the WGI with outline information in a digital vector format (Kargel et al. 2005, Raup et al. 2007a).

In principle, this aim is achievable as Landsat TM/ETM+ data of glaciers exist from all around the world and applicable ASTER data become increasingly available. The developed methods for automated and thus efficient glacier mapping and characterization (Chapters 2, 3, 4, and 5) are applicable to nearly all multispectral sensors (e.g. ASTER, ETM+, IRS-1C, SPOT) that include bands in the visible and shortwave infrared (SWIR; though we note that ASTER's SWIR subsystem failed in 2008). Under good conditions, the spatial resolution of relevant SWIR bands (20 to 30 m) allows mapping of glaciers as small as 0.05 to 0.02 km^2 in area, which is sufficient for a detailed glacier inventory of even very small glaciers (Paul 2007, Andreassen et al. 2008). Despite the much smaller area covered per ASTER scene compared with Landsat (one ninth the area per scene), the sensor is particularly useful for creating glacier inventories, as a DEM for extraction of topographic glacier data can be derived from its along-track NIR stereo bands (e.g., Toutin 2002, Kääb et al. 2003, Khalsa et al. 2004). The two-times higher spatial resolution in the visible and near infrared (VNIR) bands (15 m) further facilitates a number of other glaciological applications (Kääb 2005, Racoviteanu et al. 2007, Toutin 2008).

Compared with traditional glacier mapping from conventional frame camera aerial photography, in particular historic photos (with its much higher spatial resolution), the major advantages of satellite data are: the larger area covered at the same time, the possibility of automated mapping using multiple spectral bands, easier and more accurate orthorectification, the potential to convert raw data to physical units (reflectance or albedo) and the digital format of the raw data. In principal, glacier outlines derived from high-resolution sensors (1 m or better) can be more precise, but it has to be kept in mind that the accuracy of the derived glacier extent is governed less by spatial resolution, and more by snow conditions (e.g., snow hiding the glacier perimeter, especially in the accumulation area) and interpretation errors (e.g., debris-covered ice, attached perennial snow fields—Paul and Andreassen 2009). Moreover, due to a lack of contrast and spectral differentiation, mono or panchromatic images from high-resolution sensors are often much more difficult to interpret than images from multispectral sensors. An example of the ambiguity related to spatial versus spectral information is depicted in Fig. 1.6 for the IRS-1C and Landsat ETM+ sensor. In times of rapid glacier change it might also be more valuable to have a higher update frequency (e.g., 5 years) than a very high precision (meter accuracy) of the outline. Machine-based automatic classifications now bring tremendous capability to utilize many spectral bands simultaneously, thus far exceeding the abilities of the human eye in differentiating color and compositional units.

1.5.2 Possible applications

The available orbital sensors cover a wide range of temporal resolutions for glacier analysis (days to decades), spatial resolutions (0.5 m to 5,000 km), as well as a wide range of the spectral resolution (wavelengths from meters to nanometers). The numerous glaciological applications emerging from this variety of sensors are not discussed here, but detailed overviews can be found in Williams and Hall (1993, 1998), Bindschadler et al (2001), Kargel et al. (2005), Bamber (2006), Rees (2006), and the IGOS cryosphere theme report (IGOS 2007). Moreover, numerous applications are discussed in the regional chapters of this book and widely found in the literature (e.g., Haeberli and Hoelzle 1995, Dyurgerov and Meier 2005, Evans 2006, Raper and Braithwaite 2006).

Regarding the monitoring strategy of GTN-G, the principal thrust of satellite observations is applied towards detailed assessments (individual glaciers) at regional scales (i.e., entire mountain ranges) in typical time periods of 5–10 years. The observations include changes in glacier length, area (repeat inventories), and volume (geodetic mass balance) to allow extrapolation of related field measurements in space and time, and to validate them. Besides the possible extension of the relatively small sample of ground measurements in most regions of the world (cf. WGMS 2008), a particularly useful application at the regional scale is the evaluation of the representativeness of the glaciers selected for field measurements (e.g., mass balance) for an entire mountain range (Paul and Haeberli 2008). Other useful advanced satellite-derived products include snow cover extent at the end of the ablation period and glacier velocity fields from repeat pass data. In principle, all these products can be derived from optical satellite data, but glacier velocities and in particular DEMs (e.g., the SRTM DEM) are also obtained from microwave data (e.g., Rabus et al. 2003, Strozzi et al. 2008).

For precise measurements of glacier elevation changes, airborne laser scanning or altimetry is increasingly used (Arendt et al. 2006, Geist and Stötter 2008). LiDAR data from spaceborne instruments (e.g., ICESat) were also used to test the accu-

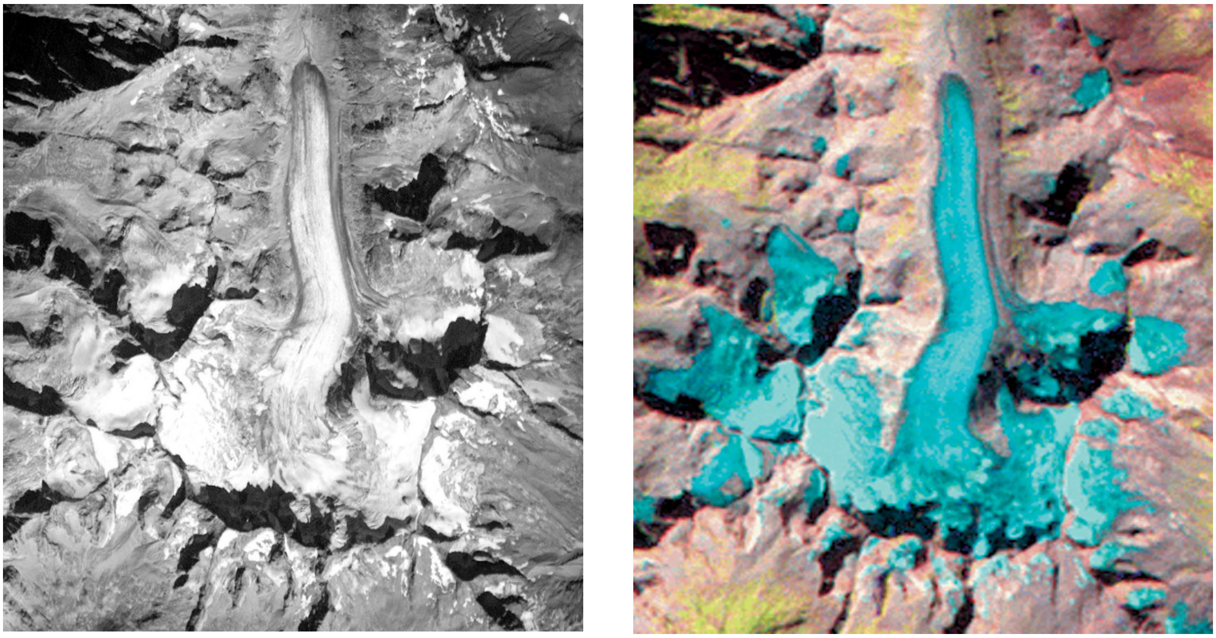

Figure 1.6. Comparison of spatial resolution versus spectral information for Forno Glacier in southwestern Switzerland. (a) Despite the higher spatial resolution (here 10 m) of the IRS-1C image many glaciers are barely recognizable in the panchromatic band. (b) The Landsat TM image has a lower spatial resolution (here 25 m), but all glaciers can be identified clearly in this false-color composite with SWIR–VNIR bands 5, 4, and 3 as RGB. IRS-1C data were obtained from the Swiss NPOC.

racy of DEMs from other sources (e.g., Kääb 2008) or to determine elevation changes at orbit-crossing points (e.g., Slobbe et al. 2008). Value-added products can be created when such products are combined. For example, glacier outlines and a DEM can provide for topographic glacier inventory data, or mapped snow extent and glacier outlines gives accumulation area ratios (AARs). Related methodologies have been explored, applied, and documented within the framework of European Space Agency (ESA) projects called GlobGlacier and Glaciers Climate Change Initiative (Paul et al. 2009). In any case, ground observations remain mandatory for calibration and validation of satellite data (IGOS 2007).

1.5.3 Challenges

The most important challenges in the use of optical satellite data for glacier mapping and monitoring are: (a) frequent cloud cover and seasonal nonglacial snow, (b) debris-covered glacier parts, (c) definition of the glacier entity, and (d) comparison with former inventories or with field measurements (e.g.. length change, mass balance). A recent overview with proposed solutions is given by Paul and Andreassen (2009) and Racoviteanu et al. (2009). Further examples can be found in the regional chapters of this book. The best recommendation to overcome point (a) is to invest time in selecting the best available images for processing, and use mosaicking of multiple scenes when cloud cover is hiding parts of the glaciers, instead of using cloud-free scenes with seasonal snow. Mosaicking, however, results in an image with an "averaged" time stamp from the selection of multitemporal images applied. For point (b) a number of semi-automated mapping methods have been developed (e.g., Paul et al. 2004), but expert manual delineation on contrast-enhanced and false-color composite imagery still provides the best results. The GLIMS guidelines by Raup and Khalsa (2010) provide detailed instructions for defining a glacier entity (point c). In most cases, a quality DEM is needed for a clear separation of ice and snow facies, and adjacent glaciers in the accumulation region. Comparison with previous datasets for change assessment (point d) can only be performed when the same entities or measurements are compared. This generally requires that the respective datasets are available in a digital format and are accurately georeferenced.

Despite the magnitude of these hurdles, in view of the ongoing efforts from the GLIMS initiative and ESA's GlobGlacier and Climate Change Initiative glacier projects, we are confident that most of the challenges can be solved and a more complete dataset of global glacier coverage can be realized within the next few years.

1.6 INTEGRATIVE GLACIER CHANGE ASSESSMENTS

The numerous length change series together with the positions of moraines give a good qualitative overview of global and regional glacier changes since their Little Ice Age maximum extents, whereas the mass balance series provide quantitative measures of ice loss since the late 1940s. However, the relatively few glacier mass balance series cannot truly represent the changes of the global ice cover. Many regions with large amounts of ice cover are strongly underrepresented in the datasets or lack any observations whatsoever. As a consequence, the field measurements with a high temporal resolution (but limited in spatial coverage) must be complemented with remotely sensed decadal area and volume change assessment (e.g., Rignot et al. 2003, Larsen et al. 2007, Paul and Haeberli 2008) in order to get a representative view of climate change impacts.

Examples for such integrative glacier change assessments for entire mountain ranges are given by Molnia (2007) for Alaska, by Casassa et al. (2007) for the Andes, by Kaser and Osmaston (2002) for tropical glaciers, by Andreassen et al. (2005) for Norway, by Haeberli et al. (2007) and Zemp et al. (2007b) for the European Alps, by Konovalov and Desinov (2007) for the Pamirs, and by Chinn et al. (2005) for New Zealand and Norway, and many others, as well as by Hoelzle et al. (2003), Zemp et al. (2007a), and WGMS (2008) for global overviews.

In addition, numerical modeling studies are used to bridge the gap between local process studies and coverage at the global scale (e.g., Raper and Braithwaite 2006), to link glacier fluctuations to climate forcing (e.g., Greuell and Oerlemans 1986), and to downscale global and regional climate modeling scenarios for use in local process models (e.g., Machguth et al., 2009).

1.7 SYNOPSIS AND ORGANIZATION OF THE BOOK

This book is broadly organized in three main categories of writing. The first category includes the Foreword (a personal perspective on the origins of GLIMS), the Prologue (a historical overview of the development of glacier science and climate change science), this introduction (Chapter 1), the book summary (Chapter 33), and Epilogue—each is an overview, a preview, or a retrospective of some broad type. The second category represented by Chapters 2–7, reviews the technology (e.g., satellites, sensors, and software) and methodological approaches to making measurements of glacier state and dynamics based mainly of satellite data. The third category, represented by Chapters 8–32, are regional chapters covering entire GLIMS regional centers or smaller areas. The regional chapters have a roughly uniform layout that includes an introduction, regional context (geologic and climatologic), case studies and special thematic topics, and summary and conclusions.

The set of technology chapters include treatments of remote-sensing science; radiative transfer, specifically in glacier materials; glacier mapping with multispectral reflectance data; DEM models, geomorphometry, and glacier mapping with DEM data; satellite image preprocessing; and the GLIMS database and comparison of analysis results. The regional chapters are generally sequenced from highest northern latitudes to highest southern latitudes, and grouped in rough accordance to the climatological and geographic structure of the Earth.

Readers will invariably draw comparisons with the massive series, *Satellite Image Atlas of the Glaciers of the World* (henceforth, *The Atlas*, Williams and Ferigno et al. 2012), which has been three decades in the making but is coming to completion the same year as this book. This book is not a more sensor-advanced version of *The Atlas*. That series is intentionally geographically complete. There is no pretense that this book is an atlas or is geographically complete, though we did make efforts to cover the full range of glacier types. Particularly lacking is much coverage of Antarctica. Other regions are missing as well. Furthermore, the types of sensors used and analysis performed varies from one chapter to another— reflecting each set of authors' preferred analysis, available data, and experience base. Thus, the result is a book containing a rich variety of methodologies, glacier types, and satellites and sensors. Indeed, we feel that this book will serve as a useful companion to *The Atlas* series. Furthermore, and highly relevant to the interpretation of glacier changes documented in this book, the quadrennially released comprehensive assessments by the Intergovernmental Panel on Climate Change provides the most thorough assessments of climate change relevant to glaciers.

Overall, as most of the 25 regional chapters show, glaciers around the globe have been shrinking dramatically since their Holocene maximum extent towards the end of the Little Ice Age. In some cases, the shrinkage in more recent years of satellite observations may include lingering responses to the end of the Little Ice Age, which in different parts of the world lasted from the 17th to late 19th centuries, and elsewhere terminated earlier in the 19th century. In other cases, such a lingering response is not possible, and the more recent decades of retreat must be due to 20th and 21st century climate change, especially with increasing rates of ice loss since the mid-1980s. On a timescale of decades, glaciers in various mountain ranges have shown intermittent readvances. However, under the present climate scenarios, the ongoing trend of worldwide and fast, if not accelerating glacier shrinkage on the century timescale is not a periodic change, and may lead to deglaciation of large parts of many mountain regions by the end of the 21st century.

This said, regional anomalies exist, no doubt indicating that climatic changes in some regions favor glacier growth. Furthermore, not all glacier variations are due to climate change. Episodic emplacement of supraglacial rock debris, especially by landslides—sometimes triggered by seismic activity—and a host of processes related to glacier calving and glacier sliding are responsible for much of the diversity of glacier changes observed in the world. Finally, among those changes linked to climate change, it is not only global warming: some parts of the planet are cooling, some are affected by changing seasonality of cloud cover, some by atmospheric aerosol pollutants; the list of variables and dynamic forcing factors is long. Global warming is at the top of the list globally, but in some places other factors are more important.

We shall return to matters dealing with the analysis of results chapter by chapter and then again more comprehensively as a synthesis within the summary chapter.

1.8 CONCLUSIONS

Many advances in our field have been made by liberal access to multispectral imaging. Free access to ASTER and Landsat has been of crucial importance. With the failure of ASTER's SWIR subsystem in 2008, we are reminded that ASTER VNIR and TIR are also aged instruments. Our research community needs adequate replacements of ASTER. Pay-per-image as provided by the commercial satellite imaging industry is not an adequate replacement.

Our research field and this book are not only about bytes of data and the digital processing of them. It is about public understanding of important matters. If socioeconomic progress is to be made on crucial issues, and if nations and economies are to avoid implosion from gross misunderstanding of publicly relevant science, the media and general public must come to recognize that climate change and its myriad impacts are complex, that it's different than weather or a year's anomalous change of a glacier, and that it is spatially heterogeneous and temporally nonlinear. This changed public perception will not happen spontaneously. Scientists must bear the burden of making this awareness and understanding happen. Scientists must become better communicators about uncertainty, error analysis, and—above all—complexity; furthermore, scientists must learn better how to draw generalizations where possible, and how to explain to the public the significance of complexity where a problem defies easy generalization. If this book does anything, we hope it shows that while the world of glaciers is complex, there are clear connections to climate that are worth the public's attention.

The challenges of monitoring the fast changes of globally distributed glaciers can only be faced by a strong, operational monitoring service with a multilevel monitoring strategy that integrates reconstructions of glacier states and fluctuations, in situ observations, and remote sensing. This monitoring effort must have a well-organized international structure, a powerful data collection, storing, and distribution architecture, and a secure financial basis from national and international sources. Thus, while GLIMS has so far relied largely on volunteerism, this endeavor requires a dedication of time and energy amounting to many, many careers. The spirit of volunteerism that has nourished GLIMS is centered in this community's perspective on data: it is the open-access movement, where we volunteer to give up (or share in) our ownership of much of our intellectual property in the best interests of our science community, our nations, of global civilization—indeed of the planet itself.

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