13.10 Glacial Responses to Climate Change

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Glossary

Calving (of glaciers) Breaking off of ice from the front of glaciers into water; the term "dry calving" is sometimes used for the same process but without water (generating ice avalanches).

Calving instability Rapid retreat and disintegration of glacier tongues ending in deep waters of the sea (tidal glaciers) or of lakes, once their (calving) front looses contact with subaquatic moraines or rock thresholds forming shallow water.

Cryosphere The domain of snow and ice on Earth; including seasonal snow, sea ice, continental ice sheets, ice shelves, glaciers and ice caps, lake and river ice, daily, seasonally, and perennially frozen ground (permafrost).

Debuttresing Stress redistribution in steep valley walls as a consequence of unloading related to glacier vanishing, which can lead to long-term rock deformation and slope instability.

Essential Climate Variable (ECV) Atmospheric, terrestrial, and oceanic phenomena selected to provide key policy-relevant information from systematic monitoring as part of the Global Climate Observing System (GCOS) in support of the United Nations Framework Convention on Climate Change (UNFCCC).

Glacier mass balance Relation between gain (accumulation) and loss (ablation) of glacier mass; accumulation is predominantly through snowfall whereas ablation mainly takes place through melting of snow and ice but can also involve other processes such as calving of ice into lakes or the sea, snow erosion by wind or avalanching of ice from steep glacier parts. The latter two can result in mass gain for neighbouring glaciers. Long-term observation of glacier mass balance should combine *in situ* measurements (snow pits, ablation stakes) for high temporal resolution and process understanding with independent geodetic/photogrammetric mapping for overall volume/mass change and calibration. Values are reported as average rates of change in glacier thickness corrected for snow/ice density (unit: meter water equivalent per year).

Global Terrestrial Network - Glaciers (GTN-G) The long-term observational network responsible for the worldwide monitoring of glacier changes within GCOS. It is run in cooperation by the World Glacier Monitoring Service (WGMS; mainly *in-situ* measurements), the Global Land Ice Measurement from Space initiative (GLIMS; remote sensing) and the National Snow and Ice Data Centre (NSIDC; data management).

Polythermal glaciers Glaciers containing ("temperate") ice at phase-equilibrium ("melting/freezing") temperature as well as ("cold") ice at lower temperatures.

Abstract

The response of glaciers to atmospheric warming has become a key issue in scientific as well as public and even political discussions about human impacts on the climate system. The predominant tendency of continued worldwide glacier shrinkage may indeed constitute one of the clearest indications in nature of rapid climate change at a global scale. More than a century of systematic and internationally coordinated observations provide quantitative documentation of this development and a basis for model developments in view of possible future scenarios. Mountain ranges at lower latitudes have lost large percentages of their glacier areas and volumes since the end of the Little Ice Age. Many of them may even become largely to even completely de-glaciated already during the coming decades. Such changes have the potential to profoundly affect environmental conditions in and around cold mountain chains. Sea-level rise, changing seasonality in water supply, and local formation of new lakes reflect changes in the water cycle at global, continental, and regional to local scales. They are accompanied by rather marked changes in landscape appearance, slope stability, erosion/sedimentation, and hazard conditions. The monitoring of glaciers itself faces difficult challenges of vanishing glaciers with long-term mass-balance observations. Modern techniques of spatial modeling increasingly help with integrated analysis of observed phenomena and early anticipation of possible developments.

13.10.1   Introduction

Large areas of snow and ice are close to melting conditions and, therefore, react strongly to climate change. Historically, this fundamental principle has helped to identify the Quaternary ice ages and the related dramatic changes in climate and environmental conditions during the most recent part of the Earth history. Modern programs of systematic worldwide climate observation include glaciers as key indicators in nature and as unique demonstration objects with respect to ongoing atmospheric warming trends and possible future climatic and environmental conditions on the Earth. Within about three centuries, the perception of glaciers in the mountain landscape changed fundamentally. It started from an early perception of mountains as a threat to humans (*montes horribiles*) or holy seats of gods via a romantic view up through green, garden-like landscapes to the clean white firn and ice in a blue sky (**Figure 1**) to a striking and often used symbol of an intact human–environment relation (Haeberli, 2007). The first comprehensive scientific field studies on the ice of glaciers (**Figure 2**; Agassiz et al., 1847) soon led to the initiation of systematic monitoring toward the end of the nineteenth century (Forel, 1895). Today, satellite-born virtual perspectives using digital terrain information clearly reveal past glacier extents with their exposed moraine deposits (**Figure 3**). Glaciers and their striking changes have thereby indeed become one of the most often invoked icons of rapid and worldwide climate change (WGMS, 2008).

Melting of snow and ice under the influence of above-zero temperatures is a common experience for a great number of the people. Glacier changes as a response to climatic changes – the focus of this chapter – can therefore, not only be physically recognized but also be qualitatively understood without an academic background. The task of the related field of science is to understand, quantify, and assess what is happening with regard to ice and climate in nature. The following text emphasizes the internationally coordinated efforts to fulfill this task in view of difficult policy-relevant questions about climatic and living conditions for future generations. It starts with a short overview of the vast and rapidly progressing research field, setting the scientific scene and defining the most important challenges. Based on this, it then describes the development of coordinated worldwide glacier monitoring for more

Figure 1   The romantic view of glaciers, snow, and ice: Mont Blanc, French Alps, from Sallenches in 1802. Painting by Pierre-Louis de la Rive. Adapted from Rasmo, N., Röthlisberger, M., Ruhmer, E., Weber, B., Wied, A., 1981. Die Alpen in der Malerei. Rosenheimer, Rosenheim, with permission from Rosenheimer.

Figure 2   Early glaciologists at Unteraar Glacier: The Agassiz team in the Hôtel des Neuchâtelois (the large boulder serving as shelter) on the medial moraine of Unteraar Glacier. Lithograph after a drawing by Joseph Bettanier published by Agassiz (1840–41). Adapted from Rasmo, N., Röthlisberger, M., Ruhmer, E., Weber, B., Wied, A., 1981. Die Alpen in der Malerei. Rosenheimer, Rosenheim, with permission from Rosenheimer.

than a century, summarizes the observed changes, discusses perspectives and challenges for the coming decades, and tries to outline some of the consequences of resulting environmental impacts in view of possible adaptation options.

13.10.2   Glaciers and the Cryosphere Components in the Climate System

In order to better understand the specific role of glaciers in the climate system and their response to climate change, it is useful to first consider them as part of the entire cryosphere (Table 1). Ongoing climate-related changes in snow and ice can be spectacular. Together with easily accessible information
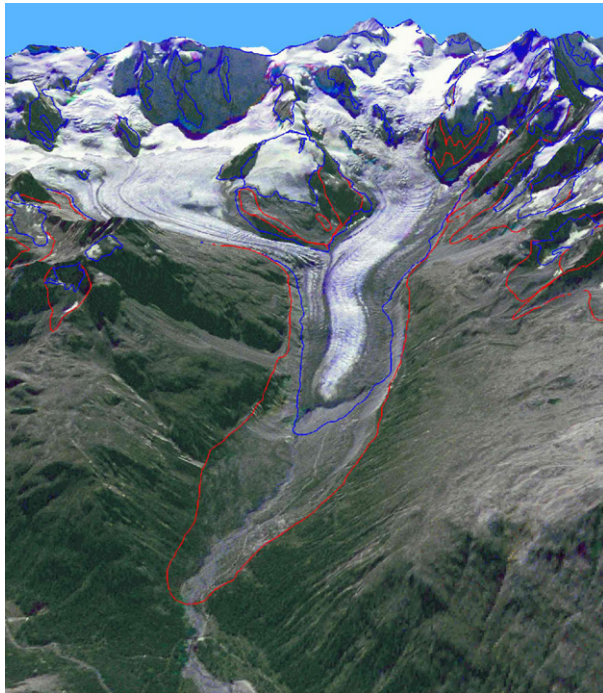
Figure 3   Oblique view of Great Aletsch Glacier, Swiss Alps. IRS-1C satellite image of 20 September 1997 (10 m resolution, black and white) fused with a Landsat image of 31 August 1998 (25 m resolution, colour) and drawn over a digital terrain model. Marked glacier extents are 1850 (red) and 1973 (blue).

from deep ice core drilling on the variability of the greenhouse effect in recent Earth history, the widespread recognition and knowledge of Arctic sea ice reduction and of worldwide glacier shrinking indeed constitute a fundamentally important source and background of the now-existing awareness with respect to questions of ongoing climate change.

Research on climate and the cryosphere is a vast scientific field in rapid progress. A number of comprehensive overviews have recently become available; among others are: Bamber and Payne (2004), Knight (2006), IGOS (2007), UNEP (2007, 2009), and Singh et al. (in preparation). The Fourth Assessment Report of the IPCC (2007a, 2007b) contains specific cryosphere chapters and deals with cryosphere aspects in various other sections such as regional chapters or chapters about sea level and paleoclimate. Snow cover, sea ice, glaciers and ice caps, and permafrost and continental ice sheets are essential climate variables (ECVs) in the Global Climate Observing System (GCOS; GCOS, 2003, 2009) that has been established in support of the United Nations Framework Convention on Climate Change (UNFCCC). Cryosphere components are interconnected in various ways. Specific aspects of change detection, attribution to causes and impacts can be summarized as follows (cf. IPCC, 2010).

With its large area covered, small volume and correspondingly high spatio-temporal variability, snow is an instable interface between the atmo-, litho-, cryo-, hydro-, and biosphere. Its albedo effect on the global radiation balance and its role in the water cycle relate snow cover to the climate system via important feedbacks and interactions (Barry et al., 2007). Observed trends (decreasing spring snow extent in the Northern Hemisphere) point to some effects from warming but they remain vague as changes in precipitation also cause changes in snow cover. Attribution to impacts concerns many parts of the climate system – especially cryospheric components and the water cycle. For glaciers and ice caps, snow is fundamentally important in that it essentially influences the mass exchange (accumulation) as well as the energy fluxes (sensible heat) via snow cover thickness in the accumulation season and radiation via albedo during the ablation season (Figure 4).

Due to its high albedo and its influence on the formation of oceanic deep water, sea ice relates to the climate system with important interactions and feedbacks (Gerland et al., 2007). The continued decrease in Arctic sea-ice extent, age, and thickness, and especially the sudden shrinking to a new record

Table 1   Components of the cryosphere

Component	Area (10^6 km^2)	Volume (10^6 km^3)	Potential sea-level rise (cm)
Snow on land (Northern Hemisphere)	1.9–45.2	<0.01	0.1–1
Sea ice (Arctic and Antarctic)	19–27	0.019–0.025	0
Ice sheets			
Greenland	1.7	2.9	730
Antarctica	12.3	24.7	5660
Glaciers and ice caps	0.51–0.54	0.05–0.13	15–37
Permafrost	22.8	4.5	7
River and lake ice	<1.0	–	–

Source: Reproduced from UNEP, 2007. Global Outlook for Ice & Snow. UNEP/GRID-Arendal, Norway, with permission from UNEP.
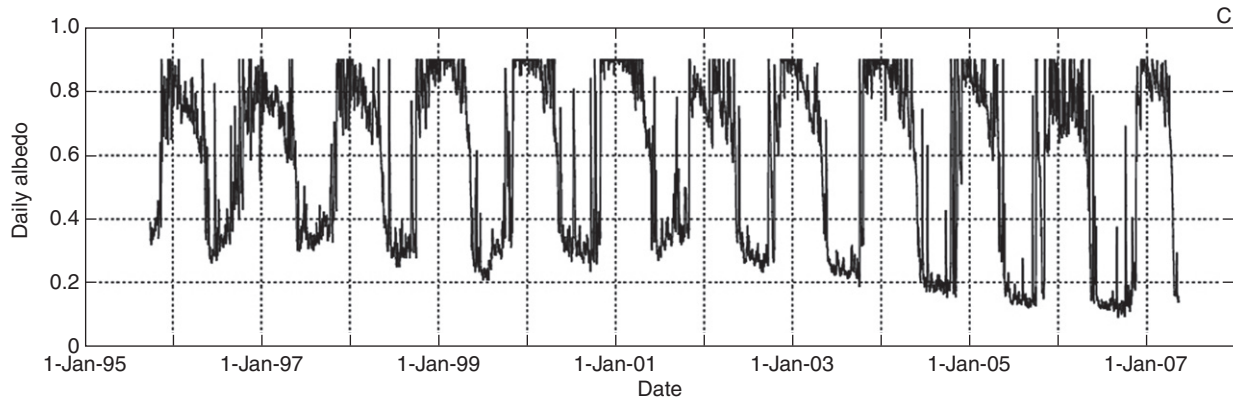
Figure 4   Change in surface albedo of the summer surface at Morteratsch Glacier, Swiss Alps. Dust input during the extremely hot and dry summer of 2003 is the main cause of the strong albedo lowering (roughly a factor of 2) of the summer surfaces in recent years. As the dust particles tend to melt into the ice and remain in place at the glacier surface, the effect lasts for extended time periods, enhancing absorption of solar radiation. Reproduced from Oerlemans, J., Giessen, R.H., van den Broeke, M.R., 2009. Retreating alpine glaciers: increased melt rates due to accumulation of dust (Vadret da Morteratsch, Switzerland). Journal of Glaciology 55(192), 729–736.

low extent in 2007, is probably the most dramatic recent change in the Earth's cryosphere, taking place at a rate that clearly exceeds the range of previous model simulations (Dorn et al., 2008; UNEP, 2009). Sea ice around Antarctica, however, shows little change – a fact that is still not fully understood. Continued sea-ice monitoring is a key element of detection strategies for global climate change. Attribution to causes is complex as the development is influenced by higher air and ocean temperatures and by particular ocean circulation patterns (acceleration of the transpolar drift in the case of the Arctic Ocean in 2007) or wind stress. The development of the Arctic sea ice is of great concern, because attribution with respect to impacts involves aspects of highest global importance such as albedo and ocean circulation as well as navigation through the northwest and northeast passages. High-arctic glaciers can have direct contact with sea ice (**Figure 5**) and can become exposed to stronger humidity advection with decreasing sea-ice extent in summer.

The two continental ice sheets, Greenland and Antarctica, are important drivers in the climate system. Slow changes in their mass balance and flow are complex and relate to centennial to millennial timescales, making attribution to causes of shorter trends difficult. Modern altimetry and gravimetry technologies are now strongly improving detection possibilities at shorter (decadal) timescales (Bentley et al., 2007). This is especially important in view of possible ice-sheet instabilities from recent flow acceleration of outlet glaciers with beds far below sea level (AMAP, 2009; Rignot et al., 2002; Vaughan and Arthern, 2007) and corresponding surface drawdown of large catchment areas (**Figure 6**). Attribution to impacts primarily relates to long-term sea-level rise and changes in the global atmosphere/ocean circulation. Probably, the clearest and most significant cryospheric information on past climate change is from ice core analysis in Antarctica and Greenland (e.g., EPICA community members, 2004). Especially high-resolution greenhouse gas and isotopic ice core records reaching 10^5–10^6 years back in time are fundamental for detection/documentation of past climatic changes and for attribution of corresponding causes. These records clearly

Figure 5   Glacier on Ellesemere Island in contact with sea ice. Photograph by W. Haeberli.

show the extraordinary level of modern greenhouse gas concentrations and contain quantitative evidence from the past about natural variability and ranges as well as about the magnitude of possible anthropogenic effects. Borehole temperature profiles in cold firn/ice provide independent checks on records of isotopic temperature proxies and reflect changes in atmospheric (annual) temperatures. If more systematically monitored (change of temperature at depth with time) and analyzed (numerical modeling of heat diffusion and flow effects), they would be important for detecting and attributing atmospheric warming as compared to conditions over very long time periods in the past (Robin, 1983). Transitional characteristics to glaciers exist with respect to outlet glaciers and ice shelves. The rapid disintegration and collapse of ice shelves in the Antarctic Peninsula (Scambos et al., 2000) and the almost complete disappearance of the Canadian ice shelves on Ellesmere Island (Copland et al., 2007) are well-documented changes. The anticipated progression of ice-shelf collapse toward colder parts of Antarctica forms a key element
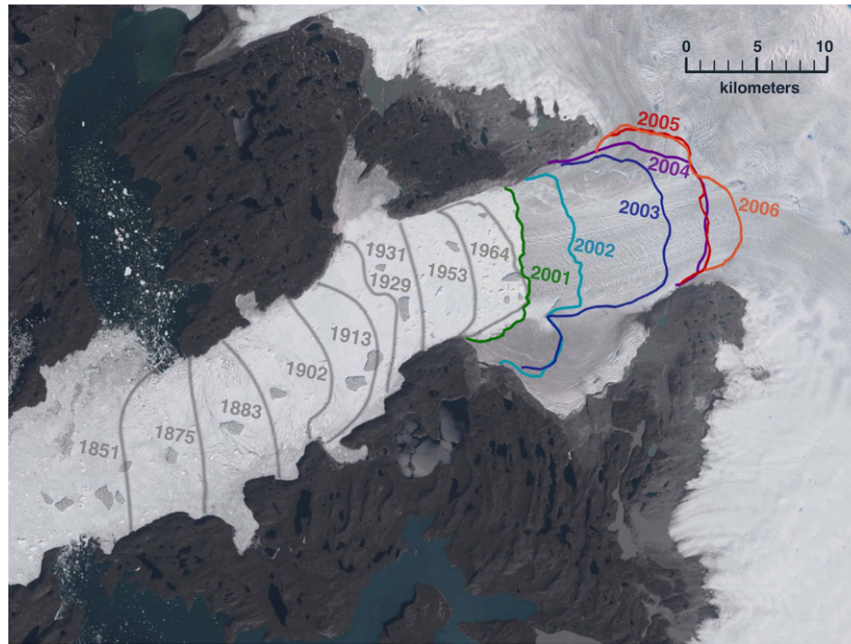
Figure 6   Retreat of Jakobshavn Isbrae between 1851 and 2006. The total backward displacement of the calving front during the twentieth century is comparable to the distance of retreat between 2001 and 2006, corresponding to an acceleration of the retreat rate by about a factor of 20. As the flow velocity roughly doubled around the turn of the millennium, the rate of ice discharge increased by about a factor of 40. Reproduced from UNEP, 2007. Global Outlook for Ice & Snow. UNEP/GRID-Arendal, Norway, with permission from UNEP.

of cryospheric detection strategies. Complex air/ocean/ice interactions make attribution to exact causes difficult, but warming as a general cause appears to be evident. Attribution to impacts concerns high-latitude marine ecosystems, the stability of outlet glaciers and ice streams in Antarctica, and, with this, indirectly long-term sea level.

Perennially frozen ground or permafrost at high latitudes is an important feedback element in the climate system (e.g., CH_4). Important information on rising ground temperatures in permafrost at high latitudes and high altitudes (mountain permafrost) as compared to historical conditions can be derived from changing subsurface temperatures and from heat flow anomalies in deep boreholes (Harris et al., 2009; Romanovsky et al., 2010). Observed changes in active layer thickness and measurements of subsidence from thaw settlement in ice-rich materials so far do not show clear trends. In both cases, attribution to climatic causes is complicated by multiple interactions of frozen ground with vegetation, snow, and surface water. Attribution to impacts involves large terrestrial ecosystems and living conditions (water resources and infrastructure) at high latitudes and slope stability and soil humidity at high altitudes (Romanovsky et al., 2007). Permafrost is intimately related to polythermal and cold glaciers in regions with dry continental-type climatic conditions (**Figure 7**), whereas temperate glaciers penetrating down to nonfrozen areas predominate in humid-maritime regions.

The duration of river and lake ice is an indicator of winter and lowland conditions, complementing summer/altitude evidence from mountain glaciers. Shortening of the season with lake and river ice in wide northern regions can be generally attributed to winter-warming effects. Highly

complex influences from short-term weather patterns (wind and precipitation/snow fall) and aquatic conditions (water circulation, groundwater influx, lake turnover, etc.) make attribution to exact causes and modeling difficult. Trafficability and ecosystem evolution are primary aspects of attribution to impacts (Prowse et al., 2007).

The shrinking of glaciers and ice caps is among the clearest and most easily understood evidence in nature for rapid climate change at a global scale and, hence, constitutes a key element of early detection strategies for global climate change. As explained in further detail below, mass-balance monitoring shows a striking acceleration of loss rates since the 1980s (Kaser et al., 2006; Zemp et al., 2009). Glacier extent (length and area) may have reached warm minimum limits of pre-industrial (Holocene) variability ranges (Solomina et al., 2008) and is far out of equilibrium conditions at many mid- and low-latitude sites. Attribution to atmospheric (summer) temperature rise as a primary cause is relatively safe as air temperature not only relates to all energy-balance factors but also to rain/snowfall and hence accumulation. Complications are due to variable englacial temperature conditions (cold, polythermal, and temperate firn/ice) and strong feedbacks (positive: albedo and elevation/mass balance; negative: adjustment of geometry and debris cover). Attribution to impacts involves landscape changes, runoff seasonality, hazards (lake outburst floods and slope instability), and erosion/sedimentation cascades (debris flows, river load, lake filling etc.). Rather surprisingly, important climatic information has recently been generated from cold/old ice patches/miniature ice caps not usually described in cryosphere overviews (**Figure 8**; Farnell et al., 2004; Haeberli et al., 2004). Dating of organic matter from disappearing
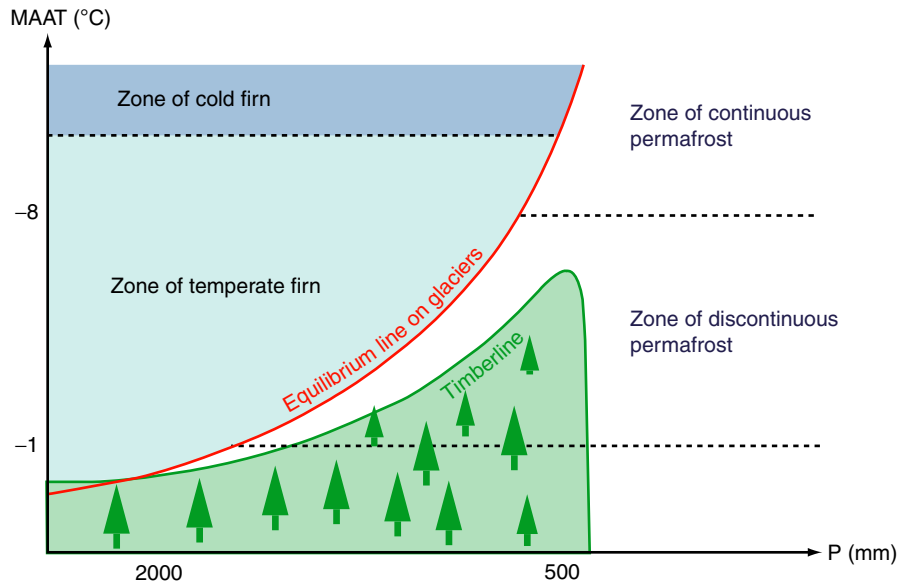
Figure 7   Scheme of glacier and permafrost occurrence as a function of mean annual air temperature and annual precipitation. Reproduced from UNEP, 2007. Global outlook for Ice & Snow. UNEP/GRID-Arendal, Norway, with permission from UNEP.
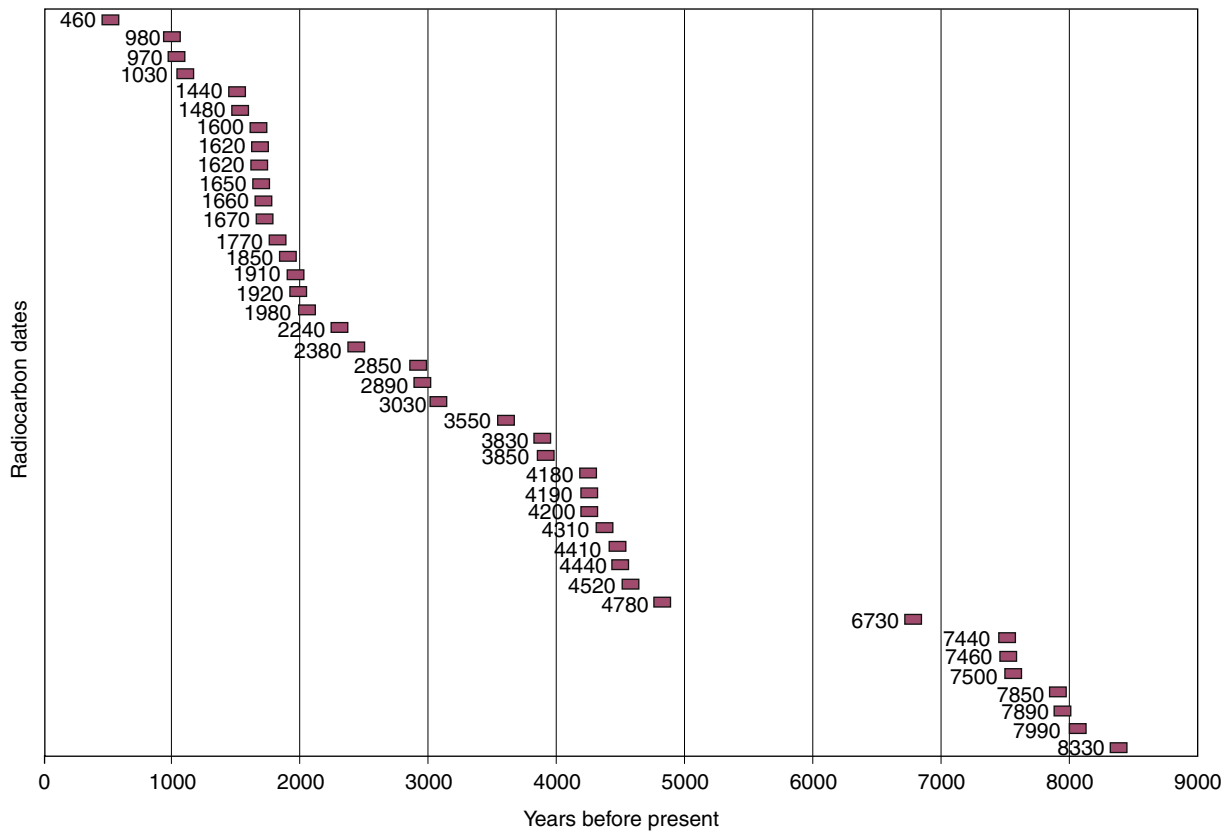
Figure 8   Age data from organic remains in vanishing perennial snowbanks (ice patches and miniature ice caps) in Southwestern Yukon, Canada. The oldest ages indicate that the extent of such ice patches is now smaller than during the past about 8000 years. Reproduced from Farnell, R., Hare, G.P., Blake, E., Bowyer, V., Schweger, C., Greer, S., Gotthardt, R., 2004. Multidisciplinary investigations of alpine ice patches in Southwest Yukon, Canada: paleo-environmental and paleobiological investigations. Arctic 57(3), 247–259, with permission from Canada Artic Journal.

ice patches with low-flow to even nonflow conditions reveals that ice (and summer air temperature?) conditions without precedence during the past five to eight millennia have now been reached in subarctic and alpine regions. Detection and attribution with respect to such phenomena need improvement.

13.10.3   The Development of Internationally Coordinated Glacier Observation

Fluctuations of glaciers have been systematically observed for more than a century in various parts of the world (Haeberli et al., 1998; Haeberli, 2005; WGMS, 2008). The early establishment of a coordinated worldwide program of data collection and dissemination greatly facilitated documentation of observed glacier changes. The evolution of this program was not without intermittent crises but nevertheless remarkably progressed over time, integrating simple observations by a large number of lay people and sophisticated scientific approaches. Rapid development of new technologies during the past decades brought along a major breakthrough with respect to monitoring strategies. This breakthrough, in turn, induced a massive enhancement of data coverage and the introduction of new data formats. Such increased methodological capacity is urgently needed to deal with rather severe challenges of observation in nature and of policy-relevant regional to global application. The following briefly summarizes primary elements of the development leading to present-day concepts and organizations.

13.10.3.1   Historical Background

The internationally coordinated collection of information about ongoing glacier changes was initiated in 1894 with the foundation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland. It was hoped at that time that the long-term observation of glaciers would provide answers to questions about global uniformity and terrestrial or extraterrestrial forcing of past, ongoing, and potential future climate and glacier changes (Forel, 1895). The monitoring strategy consisted of regular surveys at selected glacier tongues (terminus position, length change, and advance or retreat of glaciers) and also included indigenous knowledge about earlier glacier stages collected by scientists through communication with the mountain people. One important product of this golden early phase was the compilation of high-precision topographic maps specifically prepared for glaciers (Rhône, Vernagt, Guslar, Schnee, and Hintereis) in the Swiss and Austrian Alps (e.g., Mercanton, 1916). These first maps are comparable in accuracy to modern topographic maps and can therefore be used to determine long-term volume and mass changes of Alpine glaciers. Advanced technology was thus part of glacier monitoring from the very beginning, and even today these maps constitute a unique basis for scientific comparison. The mean century-scale mass-balance estimates for the European Alps (−0.2 to −0.6 m water equivalent per year) derived from them and confirmed today by modern model calculations represent a standard against which glacier changes in other mountain ranges can be compared.

During the twentieth century, the evolution of the international glacier monitoring was marked by four distinct phases. The first phase of international glacier observation, around the turn of the century, was characterized by the search for regular oscillations in the climate/glacier-system, as is illustrated by the titles of the corresponding reports (*Les variations périodiques des glaciers*). The second phase spans the two world wars and the period of economic crisis between them, when glacier observations were reduced to a minimum. As a consequence, a major glacier advance phase in the 1920s along with the following strong shrinkage in the 1930s and 1940s passed virtually unnoticed in the scientific literature. The third phase saw the reorganization of the international network under the umbrella of the UNESCO. In 1967, the Permanent Service on the Fluctuations of Glaciers (PSFG) was established. This resulted in a series of reports in 5-year intervals, the Fluctuations of Glaciers. Mass-balance data from various countries, including the Soviet Union, the United States, and Canada, were included in these reports for the first time, forming the essential link between climate fluctuations and glacier length changes. Length variation data from the United States, the Soviet Union, and other countries completed the corresponding records from the Alps, Scandinavia, and Iceland. Glacier re-advances were reported from various parts of the world, especially from the Alps, where mass balances were predominantly positive in the late 1960s and 1970s. For the first time, therefore, empirical information about glacier responses to well-documented and strong signals in mass-balance history started to become available. The fourth phase of international glacier monitoring started around the 1970s. A World Glacier Inventory (WGI) was initiated to become a snapshot of ice conditions on the Earth during the second half of the twentieth century and a temporary technical secretariat (TTS/WGI) began operations in 1976. Detailed and preliminary regional inventories were compiled all over the world to update earlier compilations (see especially Field (1975) and Mercer (1967)) and to form a modern statistical basis of global glacier distribution. The year 1986 finally saw the start of the World Glacier Monitoring Service (WGMS), combining and integrating PSFG and TTS/WGI. The new Glacier Mass Balance Bulletin was issued at 2-year intervals to speed up and facilitate access to information concerning mass balances of selected reference glaciers. International efforts were also made to collect and publish short abstracts on special events such as glacier surges, ice avalanches, glacier floods or debris flows, drastic retreats of tidewater glaciers, rock slides onto glaciers, and glacier–volcano interactions. New approaches and numerical models for analyzing characteristics of numerous unmeasured glaciers and impacts from changes in climate, energy and mass balance on the thickness, flow, and fluctuations of glaciers now became available (e.g., Jóhannesson et al., 1989; Haeberli and Hoelzle, 1995; Oerlemans, 2001; Hoelzle et al., 2003). Moreover, new programs of collaboration with advanced observational technologies (remote sensing and geoinformatics) became more and more involved (e.g., Paul et al., 2002; Bishop et al., 2004; Kargel et al., 2005).

Since the time of F.A. Forel, the first president of the International Glacier Commission, various aspects involved in monitoring have changed in a most remarkable way. Concern is now growing that the predominating trend of worldwide and fast, if not accelerating, glacier shrinkage at the century time-scale is of a noncyclic nature – there is hardly a question any more of the originally envisaged periodical variations of glaciers. Under the growing influence of human impacts on the climate system (enhanced greenhouse effect), dramatic scenarios of future developments – including complete deglaciation of entire mountain ranges – must be taken into consideration. Such future scenarios may lead far beyond the range of historical/Holocene variability and most likely will introduce processes (extent and rate of glacier vanishing and difference from equilibrium conditions) without corresponding precedence. A broad and worldwide public today recognizes glacier changes as a key indication of regional and global climate and environment change. Observational strategies established by expert groups within international monitoring programs build on advanced process understanding and include extreme perspectives. These strategies make use of the rapid development of new technologies and relate them to traditional approaches in order to apply integrated, multilevel concepts (*in situ* measurements to remote sensing and local process-oriented to regional and global coverage). Within these concepts, individual observational components (length, area, and volume/mass change) fit together and enable a comprehensive view of ongoing changes.

13.10.3.2 An Integrated Strategy

Within the framework of the terrestrial component (Global Terrestrial Observing System, GTOS) of the Global Climate Observing System (GTOS/GCOS), the Global Hierarchical Observing Strategy (GHOST) was adopted in order to connect intensive local studies on individual glaciers with coverage of large glacier samples at the global scale by integrating the following steps or tiers (e.g., Haeberli et al., 2000, 2007):

● Extensive glacier mass-balance and flow studies within the major climatic zones for improved process understanding and for calibrating numerical models. About 10 glaciers have intensive research and observation activities at this level. Storglaciären in northern Sweden (**Figures 9** and **10**), Vernagtferner in the eastern Alps, and Tuyuksu Glacier in the Kazakh Tien Shan are examples.

● Regional glacier mass changes within major mountain systems, observed with a limited number of strategically selected stakes/pits combined with precision mapping at about decadal intervals. Annual mass-balance measurements on more than 100 glaciers worldwide reflect regional patterns of glacier volume and mass changes. Attempts are currently made to fill large gaps in spatial coverage of some major mountain systems such as the Himalayas (cf. Dyurgerov and Meier, 1997) or to re-establish long observational series, which were discontinued in the 1990s.

● Long-term observations of glacier length changes. A minimum of about 10 sites within each major mountain range should be selected to represent different glacier sizes and dynamic responses. Interpretation of records over extended

(a)

(b)
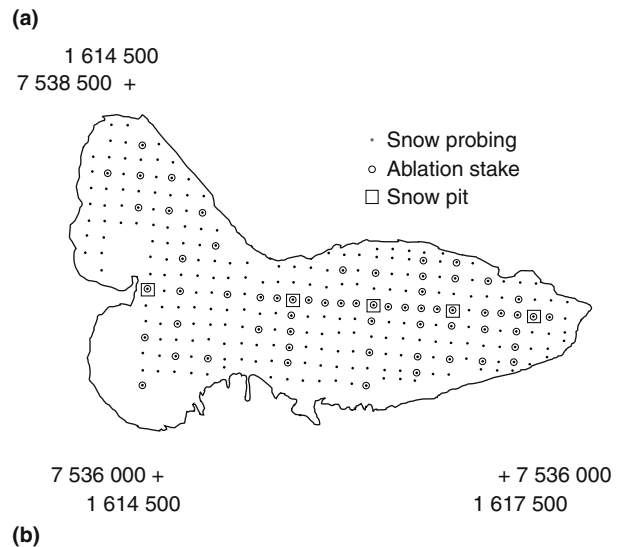
Figure 9   (a) View of Storglaciären with the summit of Kebnekaise, the highest mountain peak in Sweden. Photograph Th. Koblet (2008). (b) Observation network on Storglaciären in 2006/07. Snow-pit observations and ablation stakes are used for the determination of the winter and summer mass balance, respectively. Glacier outlines reflect conditions in 1990. Reproduced from Zemp, M., Jansson, P., Holmlund, P., Gärtner-Roer, I., Koblet, T., Thee, P., Haeberli, W., 2010. Reanalysis of multi-temporal aerial images of Storglaciären, Sweden (1959–99) – part 2: comparison of glaciological and volumetric mass balances. Cryosphere 4, 345–357. doi:105194/tc-4-345-2010, with permission from European Geosciences Union.
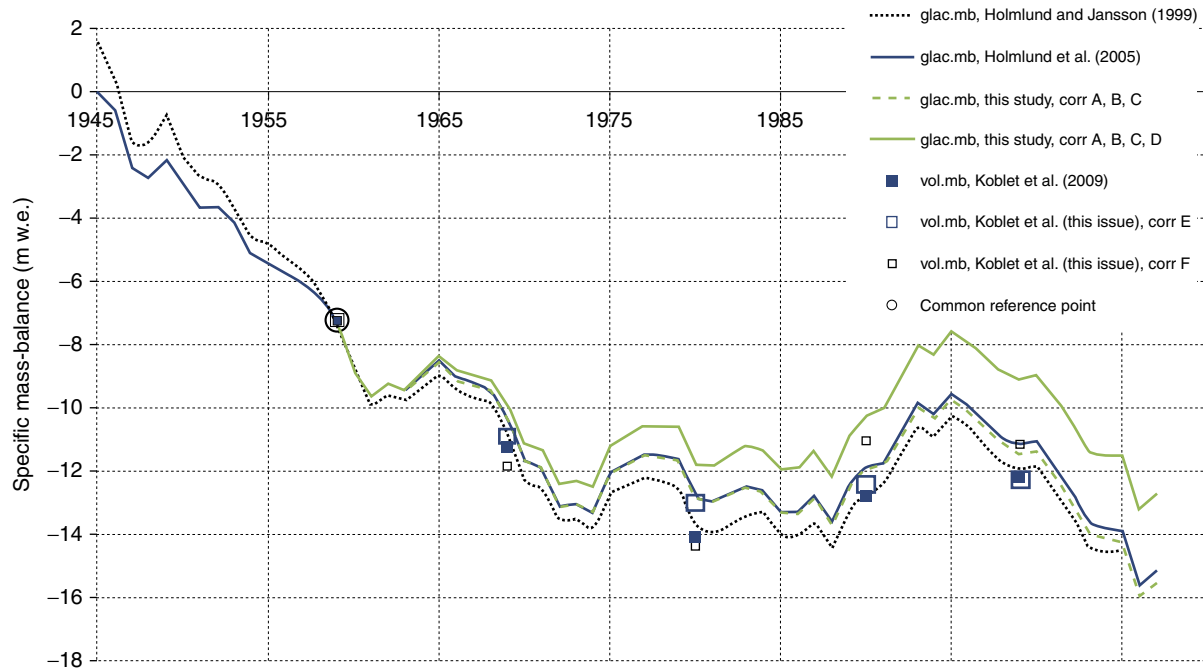
Figure 10 Cumulative glaciological and volumetric mass-balance series of Storglaciären – comparison of field measurements and repeated photogrammetric mapping (cf. Zemp et al. (2010) for details). The overall cumulative uncertainty of this intensely measured, longest glacier mass-balance time series available is about 2 m in 40 years or ca. 0.05 m y^{-1} water equivalent. The expected uncertainty for long-term mass-balance observations of 0.1 m y^{-1} cannot always be reached. Reproduced from Zemp, M., Jannsson, P., Holmlund, P., Gärtner-Roer, I., Koblet, T., Thee, P., Haeberli, W., 2010. Reanalysis of multi-temporal aerial images of Storglaciären, Sweden (1959–99) – part 2: comparison of glaciological and volumetric mass balances. Cryosphere 4, 345–357. doi:105194/tc-4-345-2010, with permission from European Geosciences Union.

time intervals best use inter-comparison (within and between regions) of geometrically comparable glaciers, dynamic fitting of glacier flow models to long time series of measured cumulative length change (Oerlemans et al., 1998), and mass-change reconstructions using concepts of mass conservation (Hoelzle et al., 2003; Paul and Svoboda, 2009).

- Glacier inventories repeated at intervals of a few decades using satellite remote sensing (continuous upgrading and analyses of existing and newly available data). Modeling of data following the scheme developed by Haeberli and Hoelzle (1995) and by digital elevation model (DEM) differencing in modern inventories with digital terrain information (e.g., Paul and Haeberli, 2008; Larsen et al., 2007; Berthier et al., 2010).

A network of about 100 glaciers representing the first and second level is established. This step closely corresponds to the data compilation published so far by the WGMS with the biennial Glacier Mass Balance Bulletin and also guarantees annual reporting in electronic form. Such a sample of reference glaciers provides information on presently observed rates of change in glacier mass, corresponding acceleration trends, and regional distribution patterns. New detailed glacier inventories are now being compiled in regions not covered in detail so far (Figure 11) or, for comparison, as a repetition of earlier inventories. This task is greatly facilitated by the launching of the Terra Satellite with its sensor ASTER and the GLIMS initiative (Kieffer et al., 2000). Remote sensing at various scales (satellite

Figure 11 Arctic glaciers on Ellesmere Island. Very little is known so far concerning such remote areas with cold/dry glaciers at high latitudes. Photograph by J. Noetzli.

imagery and aerophotogrammetry) and GIS technologies are now combined with digital terrain information (Andreassen et al., 2008; Bolch et al., 2010; Kargel et al., 2005; Kääb, 2008; Kääb et al., 2002; Paul et al., 2002; Paul and Kääb, 2005; Paul and Andreassen, 2009) in order to overcome the difficulties of earlier satellite-derived preliminary inventories (area determination only) and to reduce the cost and time of compilation.

The Global Terrestrial Network for Glaciers (GTN-G) recently established as part of the Global Terrestrial/Climate Observing System (GTOS/GCOS) is especially designed to provide quantitative, understandable, and policy-relevant information in connection with questions about process understanding, change detection, model validation, and environmental impacts in a transdisciplinary knowledge transfer to the scientific community as well as to policy makers, the media, and the public. The network is jointly operated by three operational bodies in glacier monitoring, which are the World Glacier Monitoring Service (WGMS: mainly *in situ* observations), the US National Snow and Ice Data Center (NSIDC: mainly data management), and the Global Land Ice Measurements from Space initiative (GLIMS: mainly satellite observations, now reinforced by ESA's GlobGlacier and EU's ice2sea projects) in coordination with the International Association of Cryospheric Sciences (IACS/IUGG). With a new online service, GTN-G provides fast access to regularly updated information on glacier inventory data. Currently (2010), this includes information from 100 000 glaciers mainly based on aerial photographs and outlines from 80 000 glaciers mainly based on satellite images, length change series from 1800 glaciers, mass-balance series from 240 glaciers, information on special events (e.g., hazards, surges, and calving instabilities) from 130 glaciers, as well as 12 700 photographs from some 500 glaciers. An overview report Global Glacier Changes – Facts and Figures has been published in 2008 in cooperation with UNEP (WGMS, 2008).

### 13.10.4   Documented Changes and Challenges for the Future

The tiered strategy of global glacier observations can be used to provide a systematic overview of presently available knowledge, of the extent and limitations of understanding, and of the primary challenges for the future.

13.10.4.1   Accelerated Glacier Mass Loss

Detailed process-oriented long-term mass/energy-balance and ice flow studies as carried out, for instance, at Storglaciären (Swedish Lapland; Figures 9 and 10) have formed the basis for a multitude of model studies (cf. overviews by Oerlemans (2001, 2008)). Statistical relations between meteorological parameters and measured mass balances (Reynaud and Dobrowolski, 1998) already pointed to the strong dominance of (summer) air temperature with its influence on all energy- and mass-balance parameters (cf. Ohmura, 2001; Braithwaite et al., 2003; Arendt et al., 2009), including accumulation via the solid/liquid threshold temperature. Reconstructed time series for the Northern Hemisphere (Letréguilly and Reynaud, 1990) clearly revealed the widespread, long-term, and rather simultaneous trend of glacier mass loss during the twentieth century. Degree-day models (e.g., Hock, 2005) then increasingly led to the treatment of the full energy and mass balance (e.g., Klok and Oerlemans, 2002; Oerlemans, 1991, 2010). Such models at various degrees of sophistication and complexity – even though almost exclusively for assumed

temperate firn and ice – are now widely used but still need strong tuning and highly uncertain assumptions about complex spatial patterns of snowfall and snow redistribution by wind and avalanches (cf. Machguth et al., 2006a). The treatment of numerous unmeasured glaciers, therefore, remains a major challenge (Machguth et al., 2006b, 2008). Combined mass-balance and flow models have become important instruments to study past and possible future glacier evolution (e.g., Oerlemans et al., 1998; Sugiyama et al., 2007; Jouvet et al., 2009). Like the driving mass-balance models, they also need heavy tuning of parameters (for ice deformation and basal sliding, often also for bed geometry). In connection with climate change, strong enhancement and feedback effects relate to surface albedo (Paul et al., 2005; Oerlemans et al., 2009; Figure 4) and ice downwasting or lake formation are observed (Paul et al., 2007b). The comprehensive long-term investigations of energy/mass balance and flow at a small sample of mountain glaciers indeed enabled the development of realistic numerical models of glacier mass balance, flow, and fluctuations. Despite remaining difficulties – especially concerning accumulation patterns and basal sliding – such models reflect an advanced quantitative understanding of past and present glacier evolution and enable carrying out realistic sensitivity studies with respect to potential impacts on glaciers from continued energy increase in the climate system. They also help with testing the applicability of simpler approaches for numerous unmeasured glaciers in entire mountain ranges and for scenarios of rapid climate forcing with strong feedback and enhancement mechanisms. Such simpler approaches are mostly based on considerations of mass conservation and step changes between equilibrium conditions (i.e., no transient effects); they provide maximum rates of change and remain realistic over longer time periods (dynamic response time) and with smaller glaciers (Haeberli and Hoelzle, 1995; Paul et al., 2007a; Zemp et al., 2007b).

Regional glacier mass changes within major mountain systems as measured using reduced stake networks provide information on accumulation, ablation, mass balance, and turnover at seasonal to annual time resolution. In the same way as detailed mass-balance measurements with extended stake/pit networks, they need careful calibration by repeated precision mapping, which allows for exact determination of volume/mass changes integrated over the entire glacier (Andreassen, 1999; Fischer, 2009; Thibert et al., 2008; Thibert and Vincent, 2009; Zemp et al., 2010). Laser altimetry combined with a kinematic Global Positioning System (GPS) started to replace photogrammetric mapping and can be applied for monitoring thickness and volume changes of very large glaciers which are the main meltwater contributors to ongoing global sea-level rise (Arendt et al., 2002, 2006; Meier et al., 2007; Berthier et al., 2010). Dyurgerov and Meier (2005), Kaser et al. (2006), Meier et al. (2007), Cogley (2009), and Zemp et al. (2009) recently reviewed the existing data. The past decades show a clear accelerating trend of mass loss (Figure 12). Mass balances from 30 reference glaciers with continuous observational series since 1976 reported in the biennial Glacier Mass Balance Bulletin issued by the World Glacier Monitoring have been –0.14 m water equivalent (w.e.) during 1976–85, –0.25 m w.e. during 1986–95 and –0.58 m w.e. during 1996–2005. Because unchanged climatic
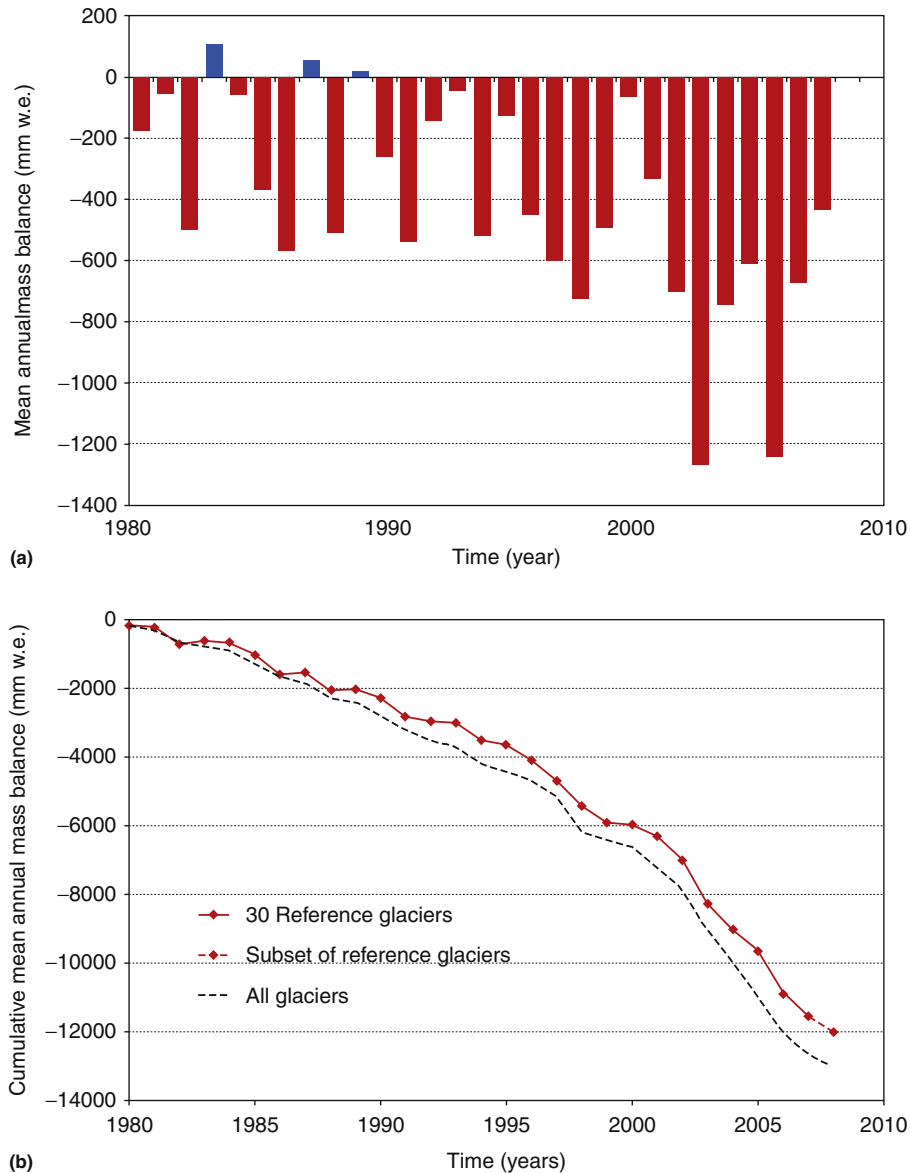
Figure 12   Average annual (a) and cumulative (b) glacier mass balances from 30 reference glaciers in nine mountain ranges. The black line in (b) is the mean value calculated for all reported mass balances irrespective of the length of the time series. Reproduced from WGMS website 2010 (http://www.wgms.ch/), with permission from World Glacier Monitoring Service.

conditions would cause mass balances to approach zero values after some time, constantly nonzero mass balances reflect continued climatic forcing. The observed trend of increasingly negative mass balances is consistent with an accelerated trend in global warming and correspondingly enhanced energy flux toward the earth surface. For the same reason, comparably high melt rates around the middle of the twentieth century would have been considerably smaller with the glacier area becoming progressively reduced in the meantime. There is an important spatio-temporal variability over short time periods: glaciers around the North Atlantic, for instance, exhibited mass increase during the recent past (1990s) and the sensitivity of mass balance and meltwater runoff from glaciers in maritime climates is generally up to an order of magnitude higher than for glaciers in arid mountains (Oerlemans and

Fortuin, 1992). Statistical analysis indicates that spatial correlations of short-term mass-balance measurements typically have a critical range of about 500 km (Cogley and Adams, 1998; Rabus and Echelmeyer, 1998) but tend to increase markedly with increased length of time period under consideration (as it applies to meteorological variables in general). Decadal to secular trends are comparable beyond the scale of individual mountain ranges with continentality of the climate being the main classifying factor (Letréguilly and Reynaud, 1990) besides individual hypsometric effects (Furbish and Andrews, 1984; Tangborn et al., 1990). Carefully calibrated modeling backwards into the final phase of the Little Ice Age confirms large variability even within short distances (Huss et al., 2008a; **Figure 13**), most probably caused by effects from individual hypsometric influences. Over such
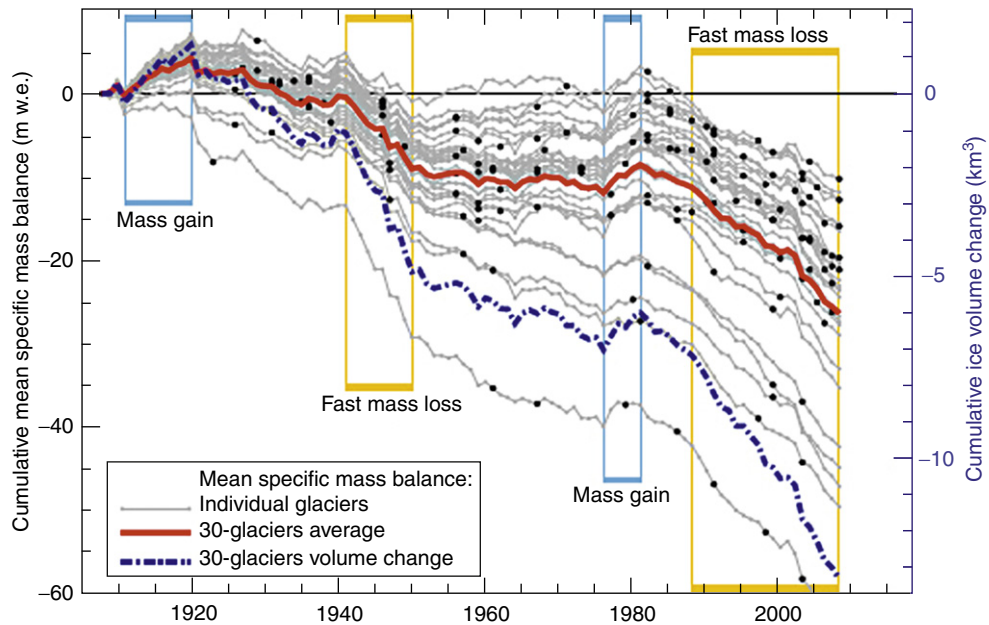
Figure 13 Cumulative mean glacier mass balances of 30 Swiss glaciers and their total cumulative volume change. Two short time intervals with intermittent mass gain (blue) and two time periods with especially fast mass loss (yellow) are marked. Reproduced from Huss, M., Hock, R., Bauder, A., Funk, M., 2010. 100-year glacier mass changes in the Swiss Alps linked to the Atlantic multidecadal oscillation. Geophysical Research Letters 37, L10501, with permission from AGU.

extended timescales (about 150 years), decreasing glacier area accompanying long time series of mass loss appears to have compensated about 50% of the mass loss, which would have taken place with constant unchanged area (Nemec et al., 2009; Paul, 2010).

13.10.4.2 Predominant Worldwide Glacier Retreat

Fluctuations in glacier length are easily determined but involve the full complexity of dynamic glacier response to climate change. The cumulative advance/retreat of glacier margins indeed represents a delayed, filtered, and enhanced signal of climate forcing. Considered over time periods corresponding to the dynamic response time for full adjustment to changed climatic conditions, cumulative length changes can be quantitatively related to the mean mass balance (Haeberli and Hoelzle, 1995; Haeberli and Holzhauser, 2003; Hoelzle et al., 2003). They are the key to quantitative comparison with past glacier changes and for a long time constituted the only possibility for assessing how representative the more direct signal from the few measured mass balances are. Combined mass-balance and flow models also help with interpreting past glacier changes with respect to global warming and sea-level rise (Oerlemans, 2005; Oerlemans et al., 2007; **Figure 14**). The spectacular retreat of most glaciers during the past 100–200 years has been recognized by the public as well as by policy-related organizations far beyond scientific circles. It is among the clearest – if not the clearest – indication in nature that climatic conditions have been changing rapidly and at a worldwide scale (IPCC, 2007a). One of the most remarkable phenomena in this context may be the homogeneity of the signal as observed especially since the latest part of the twentieth century (**Figure 15**). Special conditions, which
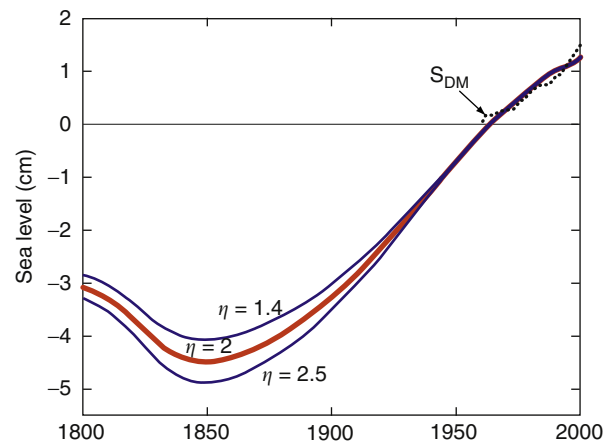
Figure 14 Reconstruction of the glacier contribution to sea-level change based on data about cumulative glacier length change. Values for η denote different length/volume scaling and the dots (S_{DM}) show the cumulative effect of global annual mass balance as calculated by Dyurgerov and Meier (2005) from observations. Reproduced from Oerlemans, J., Dyurgerov, M., van de Wal, R.S.W., 2007. Reconstructing the glacier contribution to sea-level rise back to 1850. Cryosphere 1, 59–65, with permission from Cryosphere.

limit possibilities of climatic interpretation, are related to extraordinary flow conditions (calving instability and surges), heavy debris cover (enhancing the delay in response), avalanching, or accelerated retreat induced by lake formation (Yde and Paasche, 2010). Taku glacier, for instance, is one of the relatively few glaciers on the Earth, which continued to grow and advance for decades now (**Figure 16**). This is due to the fact that the glacier is in the advance stage of its
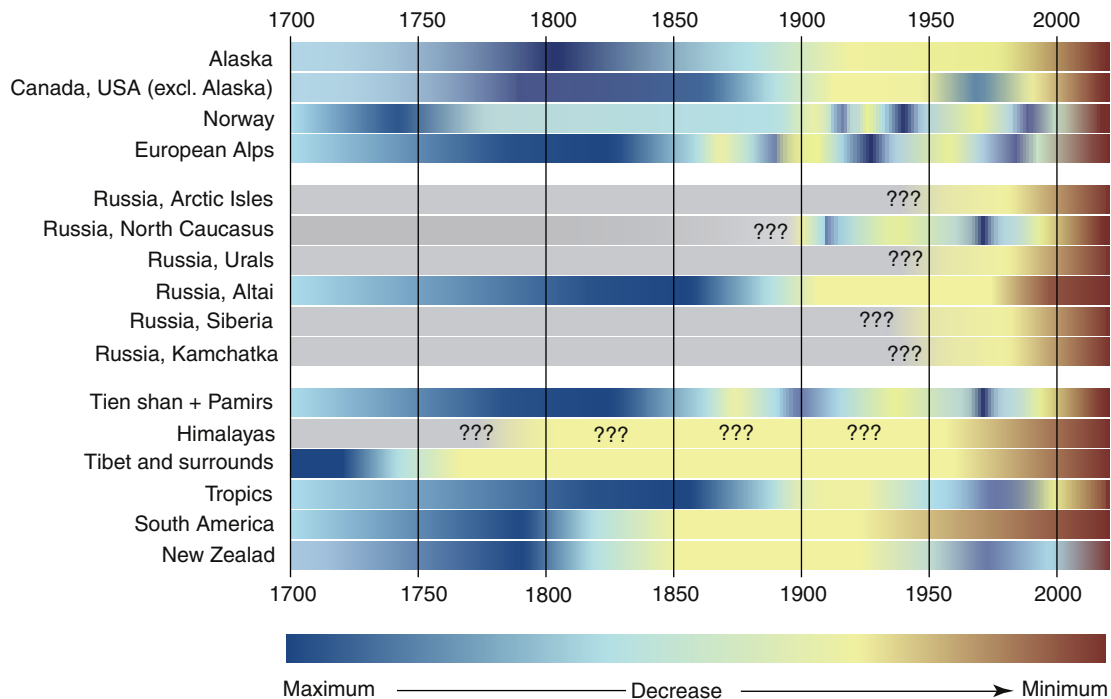
Figure 15 Glacier fluctuations (length changes and advance/retreat) since the end of the Little Ice Age. Reproduced from UNEP, 2007. Global Outlook for Ice & Snow. UNEP/GRID-Arendal, Norway, with permission from UNEP.


Figure 16 Taku Glacier, Juneau Ice Field, Southern Alaska. The glacier is in the advance stage of its calving instability cycle, advancing with its front on a delta-moraine pushed through the fjord. Photograph by W. Haeberli.

calving-instability cycle after a drastic retreat phase (Truffer et al., 2009). A thick debris cover on glacier tongues can greatly reduce the ablation near the ice margin and thereby multiply the dynamic response time, which is inversely proportional to the balance at the terminus. Heavily debris-covered glaciers can, therefore, remain in extended positions for many decades if not centuries, thereby constricting the flow of up-glacier ice (Figure 17; Schmidt and Nüsser, 2009).

Comparison with past variations can be made on the basis of moraines deposited during earlier maximum extents and of trees overridden by the ice after earlier minimum extents and now becoming exposed at retreating glacier margins. Interpretations of such facts require careful reflections about the mechanisms of dynamic glacier response, the corresponding delay with respect to mass balance and climate forcing as well as various other effects (for instance, building up of elevated morainic glacier beds). Solomina et al. (2008) explained such glaciological frameworks and provided an overview, indicating that by the first years of the twenty-first century glacier lengths and volumes have shrunk beyond variability ranges during the upper Holocene (about the past 5000 years) in many mountain ranges, and that in many cases upper (warm and energy-rich) limits of variability ranges of glacier extent and volume during even the entire Holocene may have been reached and could soon be exceeded (cf. Oerlemans and Reichert, 2002). This is especially remarkable as present-day incoming radiation on the Northern Hemisphere is considerably reduced in comparison with conditions during the early Holocene. The increasingly rapid (vertical) thickness loss combined with the delayed (horizontal) retreat now in many cases started to cause a reduction in slope- and thickness-dependent driving stress. This effect, in turn, reduces ice flux toward the glacier margins and leads to a change from an active retreat mode of glacier shrinkage to more and more widespread stagnation, downwasting, collapse, or disintegration modes of glacier vanishing (Paul et al., 2007b). A spectacular phenomenon accompanying such developments is the formation of large caves at the glacier bed (Figure 18). Increased meltwater runoff at the glacier bed melts out larger vaults in the ice above, which the reduced glacier thickness (decreasing normal stress) cannot efficiently compress any more during wintertime. Rising warm (summer) air from the glacier forefield can then better penetrate into these large caves and enhance melting of the ice roof. Quantitative effects from increased subglacial melting have hardly been investigated so far but may represent an additional positive feedback mechanism of glacier shrinking.
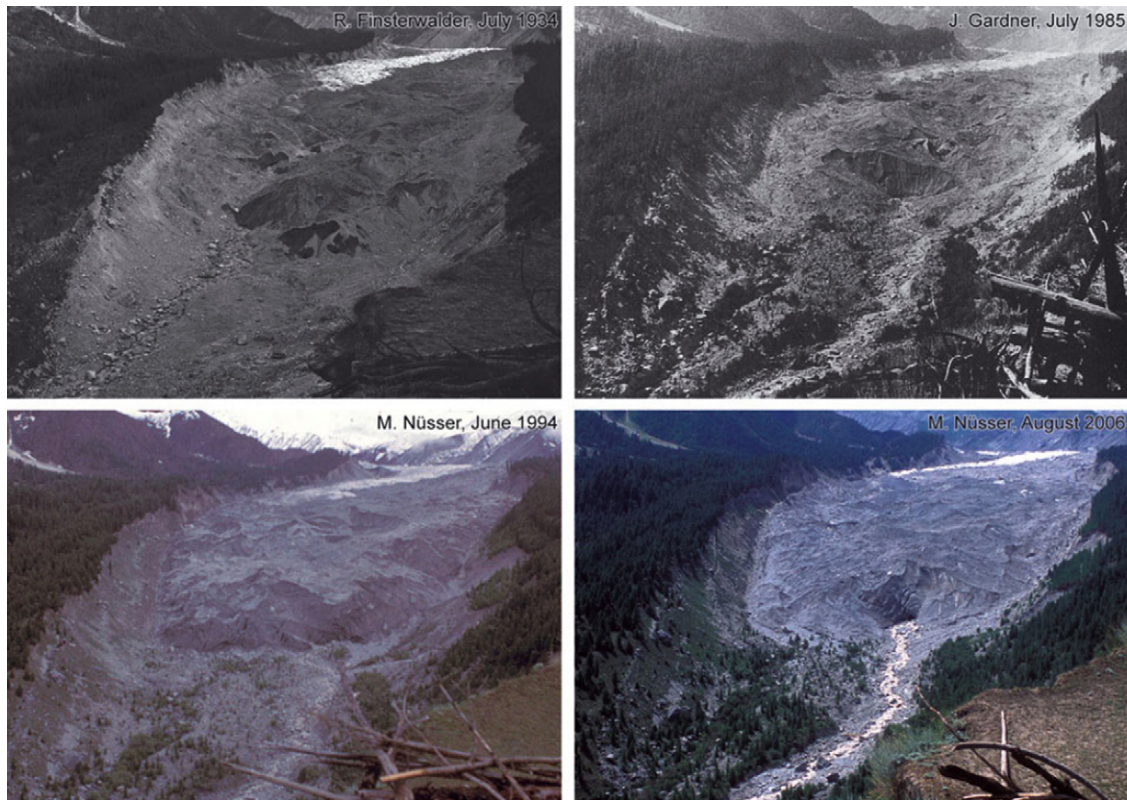
Figure 17 Repeat terrestrial photography of the Raikot Glacier terminus, Nanga Parbat, northern Pakistan, between July 1934 and August 2006. Reproduced from Schmidt, S., Nüsser, M., 2009. Fluctuations of Raikot Glacier during the past 70 years: a case study from the Nanga Parbat massif, Northern Pakistan. Journal of Glaciology 55(194), 949–959.

Figure 18 Subglacial cave at Morteratsch Glacier, Swiss Alps. The thin ice of the tongue (reduced normal stress) cannot close – in wintertime – the large channels melted out in the basal ice in summer time. Ablation underneath the glacier starts to increase due to enhanced inflow of warm air. Photograph by J. Alean.

13.10.4.3   Shrinking of Glaciers in Entire Mountain Ranges

Quantitative information from detailed glacier inventories compiled during the second half of the twentieth century mainly concerns four parameters: highest and lowest elevation, area, and length. Already with these four basic parameters and some additional topographic and climatic data,

important characteristics of numerous glaciers in entire mountain ranges can be derived. Based on a corresponding parametrization scheme, Haeberli and Hoelzle (1995) analyzed the entire sample of glaciers > 0.2 km^2 of the European Alps around 1975 with respect to the frequency distribution of surface area (maximum occurrence: 0–5 km^2), mean altitude or mid-range elevation (2800–3000 m a.s.l.), overall slope (20–25°), mean basal shear stress (40–80 kPa), slope- and stress-dependent mean ice thickness (a few tens of meters), mean flow velocity (0–30 m y^{-1}), reaction time as the delay of tongue length-change onset with respect to marked changes in mass balance (10–20 years), dynamic response time for full adjustment to changed mass-balance conditions (20–40 years), relaxation time as the difference between response and reaction time (10–20 years), as well as probabilities of temperate, polythermal, and cold ice occurrence, or relations with periglacial permafrost. Such numbers immediately make it clear that the great majority of glaciers in mountain ranges comparable with the European Alps are small, steep, thin, close to or at melting temperature and, hence, highly vulnerable to even small increases in atmospheric energy content. Based on a combination of mass balance and inventory data, glaciers in the European Alps are now estimated to have lost about half their total volume (roughly –0.5% per year) between the end of the Little Ice Age (1850) and 1975. Roughly another 10% (20–25% of the remaining amount) probably melted away between 1975 and 2000 and again within the first decade (2000–09) of the twenty-first century,

corresponding to about –2% per year of the remaining volume (updated after Haeberli et al. (2007)). With future human-induced atmospheric warming, almost complete deglaciation could occur within decades (Zemp et al., 2006), leaving only some ice remains on the very highest peaks and in the thickest but downwasting rather than retreating glacier tongues. Advanced stages of such developments are documented on tropical mountains (Ceballos et al., 2006; Cullen et al., 2006; Klein and Kincaid, 2008).

Modern inventories combined with digital terrain information open a wealth of new possibilities. One of the most promising aspects is that slope- and stress-dependent ice thickness can now be calculated at pixel resolution for large numbers of glaciers (Farinotti et al., 2009), and digital terrain models without glaciers can be produced for entire, now still glacierized mountain ranges (Linsbauer et al., 2009). Together with *in situ* measurements of glacier mass balance, satellite-derived quantitative information about glaciers in entire mountain ranges is becoming the core of future-oriented worldwide glacier monitoring. Spectacular results have already been obtained from DEM differencing, reflecting changes in surface elevation at pixel resolution for large regions (Larsen et al., 2007; Bolch et al., 2008; Berthier et al., 2010; Paul and Haeberli, 2008). The application of such techniques to mountain ranges all over the world can help to greatly improve assessments of sea-level rise contributions from glaciers and ice caps.

13.10.5   Scenarios, Impacts, and Adaptation

With plausible/realistic scenarios of climate evolution (2–6 °C increase of air temperature by the end of the twenty-first century over pre-industrial conditions), the Earth's glacier cover could be dramatically reduced within the coming decades. Consequences of glacier disappearance are likely to be strongly felt in connection with the water cycle, landscape evolution, geomorphological processes, and natural hazards, the latter three having especially strong interrelations. Moreover, the monitoring of glacier change itself also may face considerable challenges.

13.10.5.1   Glacier Vanishing and Water

Glacier changes affect the water cycle at global, continental, and regional/local scales. At global scales, sea-level rise constitutes the main concern (Church et al., 2007). The total contribution to global sea-level rise of glaciers and ice caps other than the continental ice sheets of Antarctica and Greenland is estimated at a few tens of centimeters (Oerlemans et al., 2007; **Figure 14**) and most likely continues far into our century to constitute a primary source of sea-level rise (Meier et al., 2007). Extrapolation of available mass-balance measurements has been used in various studies for estimating annual rates of sea-level rise due to glacier melt (Bahr et al., 2009), increasingly combined with DEM-differencing over large glacierized regions (Berthier et al., 2010). The growing difference from equilibrium conditions must thereby be considered. The assumption that the mass balance of a glacier is fairly well decoupled from the dynamic response of the glacier and primarily constitutes a direct

signal of climatic conditions at the site is reasonable only for relatively steep glaciers with a short response time and remaining relatively close to steady state (cf. Haeberli and Hoelzle (1995) for the slope dependence of the response time) and/or for slow climate forcing. With accelerating climate change, various feedbacks come into play. Size effects (small/large glaciers), thermal aspects (cold/temperate firn areas), positive feedbacks (albedo and surface elevation), and process changes (rock outcrops/collapse/lake formation) are especially critical. Size effects concern the different response characteristics of small and often more steeply inclined glaciers with short response times and large/mostly flat glaciers with long response times. As the latter cannot retreat quickly enough and lose exposed areas through time, rapid forcing leads to positive feedbacks related to changes in surface elevation (mass-balance/altitude feedback), which are cumulative and – after some time – tend to completely dominate thickness change (Raymond et al., 2005) and to induce runaway effects (downwasting and collapse, cf. the results of DEM differencing by Larsen et al. (2007), Paul and Haeberli (2008), and Schiefer et al. (2007)). As a consequence, even under comparable climatic conditions, results from mass-balance measurements on small glaciers (Cogley and Adams, 1998; Dyurgerov and Meier, 1997; Kaser et al., 2006) may not, therefore, be extrapolated in a simple straightforward way to large glaciers. This is especially important with respect to estimates of sea-level rise as caused by the melting of the largest glaciers on the Earth (Haeberli, 2005). As an additional effect, some large glaciers terminate in deep ocean water or in local lakes, causing calving instability or even (partial) flotation and dynamic thinning (**Figure 19**; Meier et al., 2007) but do not contribute to global sea-level rise with their parts below the water level. With accelerated forcing, more and more medium-size to small glaciers with shorter response time are likely to undergo similar process changes far from equilibrium conditions, a fact which makes extrapolation in time difficult (cf. Le Meur et al., 2007). Extrapolation in time is also made difficult, because cold firn areas in regions with a dry-continental climate (cf. Zemp et al., 2007a) or at high

Figure 19   Sawyer Glacier, Stikine Ice Field, Southern Alaska. The glacier is in the rapid retreat phase of its calving instability cycle. It has shortened by about 35 km since its maximum extent reached probably during the Little Ice Age. Photograph by W. Haeberli.

altitudes (Suter et al., 2001; Vincent et al., 2007) may warm up, become temperate, start losing mass from large parts of their accumulation area and, hence, strongly increase their mass-balance sensitivity with respect to atmospheric warming. Moreover, many heavily glacierized regions in the Arctic can be classified as ice caps or ice fields with a limited altitudinal range. The latter implies that they could quickly melt down once a critical threshold in the climate is passed (Nesje et al., 2008).

At continental scales, the changing runoff seasonality in water supply from large rivers results from time shifts in snowmelt and from disappearing glaciers. Seasonal changes in available water resources due to enhanced melting of snow and ice are among the most important socio-economic implications of climate change effects on glaciers. This is especially true for semi-arid regions such as they exist in Central Asia or parts of the Andes (Bradley et al., 2006). As compared to a 1961–90 reference period, Juen et al. (2007) modeled a ~10–20% runoff decrease in the dry season for a 34% glacierized catchment in the Cordillera Blanca, Peru, depending on time horizons (2050, 2080) and emission scenarios, and a ~10–25% runoff increase during the humid season. For the European Alps it is projected that, depending on the proportion of catchment glacierization and climate scenario, summer runoff will increase for some years or decades to come due to enhanced melt rates and then sharply decline because of shrinking areas (Huss et al., 2008b). A robust projection is a general shift of mid-latitude peak runoff from summer toward spring (Figure 20). This will have profound implications for water resource management in the future, particularly for the energy and agriculture sectors. Alpine hydropower plants may start to store water in the reservoirs during winter and spring rather than summer. To avoid conflicts, the management of water resources must be improved toward more integrated, sustainable, and efficient strategies. In Peru, for instance, several conflicts over diminishing water resources have arisen in recent years between local population, farmers, and hydropower companies (e.g., Carey, 2005). More integrative concepts considering the need of different sectors are required and will have to be developed based on robust projections.

At local to regional scales, glacier thinning and retreat has led to the formation of numerous new lakes in high-mountain regions (Figure 21), and many other lakes are likely to form in the near future with continued glacier shrinkage. Methodologies have recently been developed to predict sites with over-deepened glacier beds where new lakes may form in the future (Frey et al., 2010; Linsbauer et al., 2009). These new lakes are attractive for tourism and hydropower development but may also constitute serious hazards as discussed in the following section.

13.10.5.2   Landscape, Surface Processes, and Hazards

Landscape evolution, geomorphic processes, and natural hazards as related to glacier changes are closely interconnected. A prominent phenomenon is the formation and growth of new lakes, commonly located at the terminus of the glacier or behind terminal moraines (Figure 22). The

phenomenon as such is not new, and hazards due to formation of glacier lakes have been recognized for quite a while (Evans and Clague, 1994). In fact, severe disasters were caused in the past by outbursts from glacial lakes in various high-mountain regions of the world, including the Andes (Reynolds, 1992; Carey, 2005; Hegglin and Huggel, 2008), Caucasus and Central Asia (Narama et al., 2006; Aizen et al., 2007), the Himalayas (Vuichard and Zimmermann, 1987; Richardson and Reynolds, 2000; Xin et al., 2008), North America (Clague and Evans, 2000; Kershaw et al., 2005), and the European Alps (Haeberli, 1983; Haeberli et al., 2001; Kääb et al., 2004). Glacial lakes can be classified into several types according to their position relative to the glacier and the damming mechanism (Richardson and Reynolds, 2000; Clague and Evans, 2000). The different lake types are more or less frequent in different regions of the world, depending on climatic, glaciological, topographic, geological, and other factors. In recent years, increasingly fast formation of lakes has been observed in several high-mountain regions. Rapid lake growth processes are due to positive feedback effects with the thermal energy of water enhancing the melting of ice (Kääb and Haeberli, 2001). In the European Alps, for instance, a number of rapid lake formations have been observed in recent years, including Belvedere Glacier (Macugnaga, Italy; Tamburini et al., 2003; Kääb et al., 2004), Trift, and Lower Grindelwald Glacier (see Chapter 13.17; Huggel et al., 2010; Werder et al., 2010). At Grindelwald, future scenarios suggest a continuing rapid glacier retreat with the potential of a significant enlargement of the lake. In late 2008, authorities therefore started to drill a more than 2-km-long tunnel that should enable an artificial drainage of the lake and prevent a serious lake outburst with expected damages between Grindelwald and Interlaken, ~2.5–20 km downstream. The tunnel started functioning in spring, 2010. From case studies like Grindelwald and previous ones, it has become clear that the increasing destabilization of slopes due to glacier retreat and also permafrost degradation leads to complex hazard situations with respect to high-mountain lakes, which necessarily call for an integrative assessment.

A concentration of pronounced slope stability effects related to glacier downwasting and debuttressing of rock and moraine slopes, permafrost degradation, rock fall, and debris flow activity, all interacting with the formation and growth of glacier lakes and further glacier decay, characterize the environment around the newly formed lake at the surface of the tongue of Lower Grindelwald Glacier (Figure 23). This could be a model case for increasingly destabilized future high-mountain environments. Debuttressing effects of rock slopes due to glacier downwasting may result in large rock avalanches, large-scale, progressive, and slow rock mass deformation, and frequent rock fall events (Ballantyne, 2002). The three modes of response are all consequences of stress redistribution and release and may act in a combined way. Rock slope failure is thereby commonly a result of slope steepening by glacial erosion and unloading or debuttressing due to glacier retreat (Augustinus, 1995). Many ice-related rock avalanches were recently documented around the world (Huggel, 2009). Examples are the Brenva and Triolet rock avalanches in the Mont Blanc massif in the eighteenth and twentieth centuries (Deline, 2009), the Kolka-Karmadon ice/rock-avalanche in the Caucasus (Evans et al., 2009), the Sherman
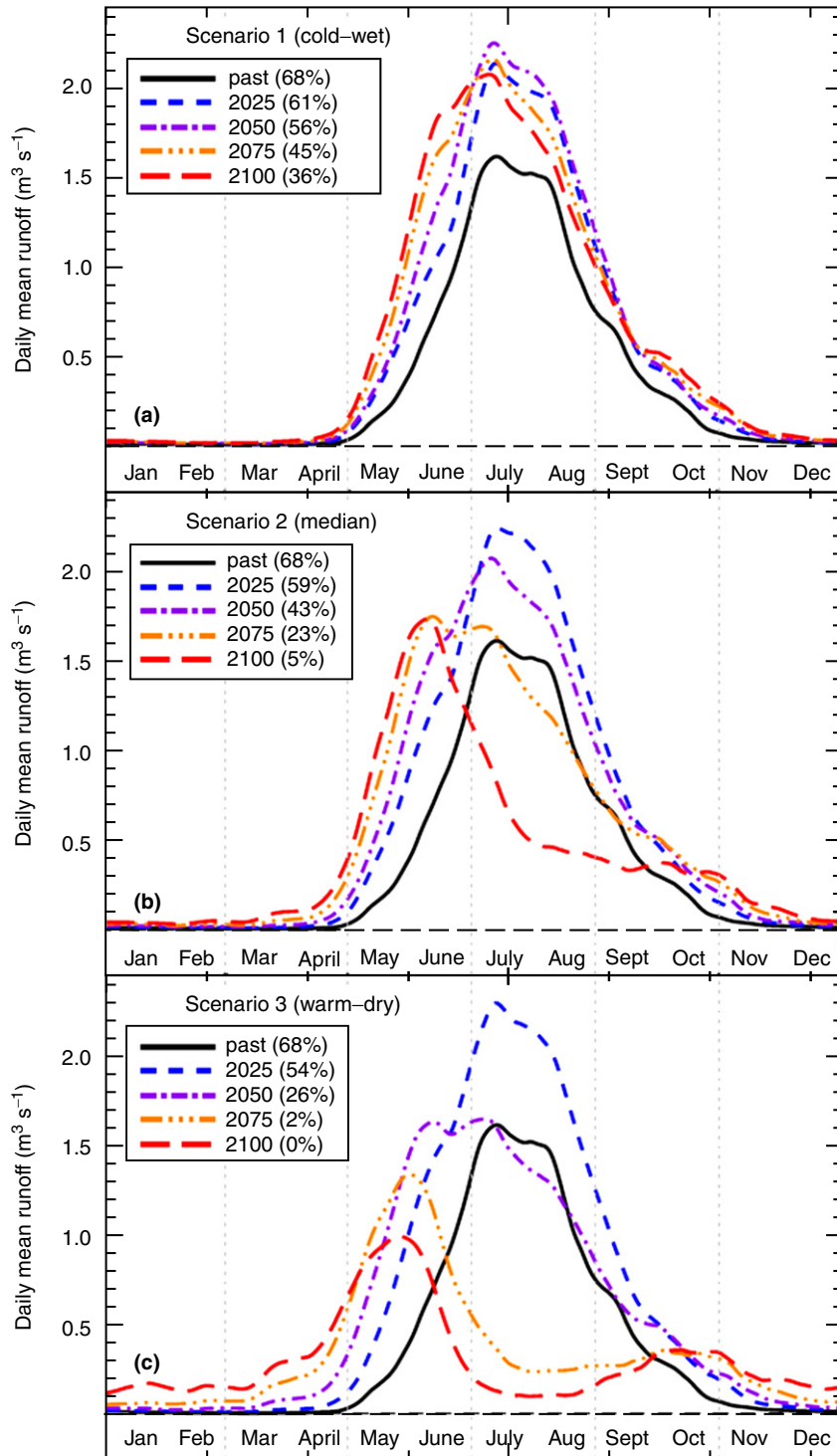
Figure 20   Annual cycle of runoff of Glacier de Moming shown for the past (1961–90) and four snapshots in the future. The glacierization of the catchment at each evaluation year is given in brackets. (a) Scenario 1 (cold–wet), (b) Scenario 2 (median) and (c) Scenario 3 (warm–dry). Reproduced from Huss, M., Farinotti D., Bauder, A., Funk, M., 2008b. Modelling runoff from highly glacierized alpine drainage basins in a changing climate. Hydrological Processes 22(19), 3888–3902. doi:10.1002/hyp.7055, with permission from Wiley.

glacier rock avalanche in 1964 in Alaska (Shreve, 1966), a significant number of rock avalanches in the Karakorum (Hewitt, 1988, 1999, 2009), and in British Columbia, Canada (Geertsema et al., 2006), just to name a few. Such rock slope failures can occur in permafrost-free conditions or the destabilization processes can additionally be affected by permafrost degradation (Fischer et al., 2006). Furthermore, they act separately or in relation with glacier lakes
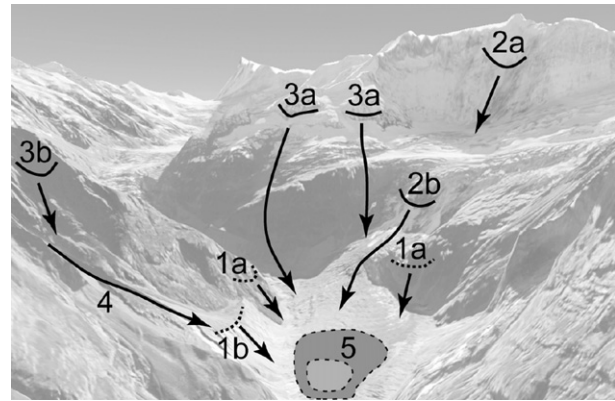
Figure 21 Laguna Milhuacocha, Cordillera Blanca, Peru. With the diappearance of the flat glacier tongue, a lake formed within the moraines of the Little Ice Age. At the same time, the stabilizing effects by the former flat glacier tongue with respect to buttressing the over-steepened valley flanks and to holding back the steep, fast flowing upper glacier parts vanished. The risk of a large ice or rock avalanche into the lake with subsequent formation of impact waves or seiches clearly increased. Photograph by E. Hegglin.

Figure 22 Proglacial lakes at Hooker and Mueller Glaciers, New Zealand. Photograph by T. Chinn.

Figure 23 An integrative perspective on different high-mountain mass movement hazards and their interactions under impacts of climate change (adapted from the situation at Lower Grindelwald glacier). Landslide in bedrock (1a) and moraine (1b) due to de-buttressing effects from glacier retreat since the Little Ice Age. Ice avalanches from polythermal steep glaciers due to increasing firn and ice temperatures (2a), and from dissected temperate steep glacier parts (2b). Rock fall and avalanches in relation with permafrost degradation (3a). Regular rock fall from areas of warm bedrock permafrost (3b) fueling debris flow (4) initiation zones. Lake formation (5) due to glacier retreat or down-wasting, posing outburst floods hazards that are exacerbated by potential impact from multiple mass movement processes. Reproduced from Haeberli, W., Clague, J.J., Huggel, C., Kääb, A., 2010. Hazards from lakes in high-mountain glacier and permafrost regions: climate change effects and process interactions. Avances de la Geomorphología en España, 2008–2010, XI Reunión Nacional de Geomorphología, Solsona, pp. 439–446, with permission from Centre Tecnològic Forestal de Catalunya.

(cf. Grindelwald), thus seriously enhancing the hazard potential due to impact waves resulting in lake outburst floods. Continued atmospheric temperature rise could imply enhanced meltwater percolation into cold firn with a widespread transformation of cold to polythermal or temperate ice on steep slopes and thus alter the potential source zones for ice avalanches (*see* Chapter 13.17; Huggel et al., 2010), because cold ice masses are stable at steeper slopes than temperate ice (Haeberli et al., 1989; Huggel et al., 2004).

The retreat of glaciers implies an increasing sediment availability, which can enhance overall erosion rates by up to an order of magnitude (Hinderer, 2001) and the potential for mass movement hazards. Since the end of the Little Ice Age, new proglacial areas with marked moraines and large amounts of poorly consolidated sediments have been uncovered, which are now prone to slope failure and large debris flows. In the Alps, some of the largest debris flows that occurred in

recent years originated from such formerly glacierized areas (*see* Chapter 13.17; Huggel et al., 2010; Zimmermann and Haeberli, 1992; Chiarle et al., 2007). At the same time, the unraveled sediment is likely to have serious implications for the management of alpine reservoir lakes connected to hydropower schemes (Boillat et al., 2003). More rapid filling of lakes by sediment and especially enhanced input of sediment into turbines leads to extremely costly maintenance, which additionally affect the operation schedule of the power schemes. Potential countermeasures against Alpine reservoir sedimentation by modification and/or stopping of turbidity currents have been analyzed recently (Oehy and Schleiss, 2007). The methods developed to detect the future location and approximate timing of formation of glacier lakes (Frey et al., 2010) can help in anticipating the multiple effects of natural hazards, sediment budgets, and water reservoirs in relation with hydropower or tourism activities.

13.10.5.3 Challenges for Monitoring Glacier Evolution

A rapidly upcoming problem in the field of glacier monitoring is the imminent vanishing of glaciers with long mass-balance records. Extensive mass-balance observations as well as less sophisticated determinations of mass changes as regional climate signals are based on studies for a limited number of small- to medium-size glaciers (Braithwaite, 2002; WGMS, 2009) with surface areas typically a few km^2, and average

thicknesses of tens rather than hundreds of meters. With yearly thickness losses increasing from characteristic twentieth-century values of a few tens of centimeters to now more than a meter, many of these glaciers are likely to disintegrate and completely vanish within the coming decades (Paul et al., 2007a; Zemp et al., 2006). Such processes could already be observed throughout the Alps (Paul et al., 2007b) and from the nine glaciers with long-term mass-balance series, some might disappear soon or have already started to disintegrate as the example of the Caréser Glacier in the Italian Alps impressively shows. The glaciers of the Alpine mass-balance network, for instance, often have mean thicknesses of a few tens of meters (Table 2). During the past quarter of a century,

they lost 20–25% of their surface area and roughly 40% of their total volume. A further increase of the equilibrium line altitude by 200 m – corresponding to a temperature rise of about 1.3 °C (Zemp et al., 2007b) – would eliminate most of their accumulation areas. Mass-balance measurements could lose their value as a climate indicator by disintegration of the observed glacier, years before the final ice remnant has melted. The disintegration of Careser Glacier since 1985 (Figure 24) is documented on Landsat imagery (Paul et al., 2007b) and has been described recently by Carturan and Seppi (2007). In order to save the mass-balance network through the near future and to guarantee continuity of the measured data, new and still higher-reaching/larger glaciers must be envisaged as

Table 2 Characteristics and changes of glaciers with long-term mass balance observations in the Alps

Name	Year	A_{70} (km^2)	A_{00} (km^2)	ΔA (%)	V_{70} 10^6 m^3	h (m)	$\sum b_{80\text{-}06}$ (m w.e.)	ΔV (%)	$\Delta A / \Delta V$	Decay time
Sonnblick* (AU)	1959	1.77	1.39	20	45	20–30	−15	55	0.36	2010–30
Vernagt** (AU)	1965	9.56	8.36	20	435	40–50	−15	30	0.66	2050– ?
Kesselwand (AU)	1953	4.24	3.85	10	255	55–65	−6	10	1	2020– ?
Hintereis (AU)	1953	9.47	7.40	20	840	80–90	−21	20	1	2100– ?
Careser (IT)	1967	4.68	2.83	40	175	30–40	−35	75	0.53	2010–30
Silvretta (CH)	1960	3.25	2.89	10	165	45–55	−15	28	0.36	2030– ?
Gries (CH)	1962	6.60	5.26	20	540	75–85	−24	25	0.80	2040– ?
St. Sorlin (FR)	1957	3.54	3.00	15	155	40–50	−24	50	0.30	2030–70
Sarennes (FR)	1949	0.90	0.50	44	25	20–30	−32	90	0.49	2010–40
Findelen	2005	19.9	15.3	23	1610	80–90	−19	21	1.1	2050– ?

Year = beginning of regular mass balance determinations, A_{70} = surface area around 1970, A_{00} = surface area around 2000, ΔA = area change, V_{70} = estimated volume in 1970, h = estimated mean glacier thickness around 1970, $\sum b_{80\text{-}06}$ = cumulative mass balance 1980–2006, ΔV = volume change from around 1970/80 to 2006, Decay time = estimated time of possible glacier disappearance, disintegration or complete loss of accumulation area. Values are rounded and rough estimates based on WGMS data and the parameterization scheme of Haeberli and Hoelzle (1995).
Source: Reproduced from Haeberli, W., Hoelzle, M., 1995. Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. Annals of Glaciology 21, 206–212, (Russian translation in: Data of Glaciological Studies, Moscow (Materialy glyatsiologicheskih issledovanii, Moscow, Russia), 82, 116–124.), with permission from IGS.
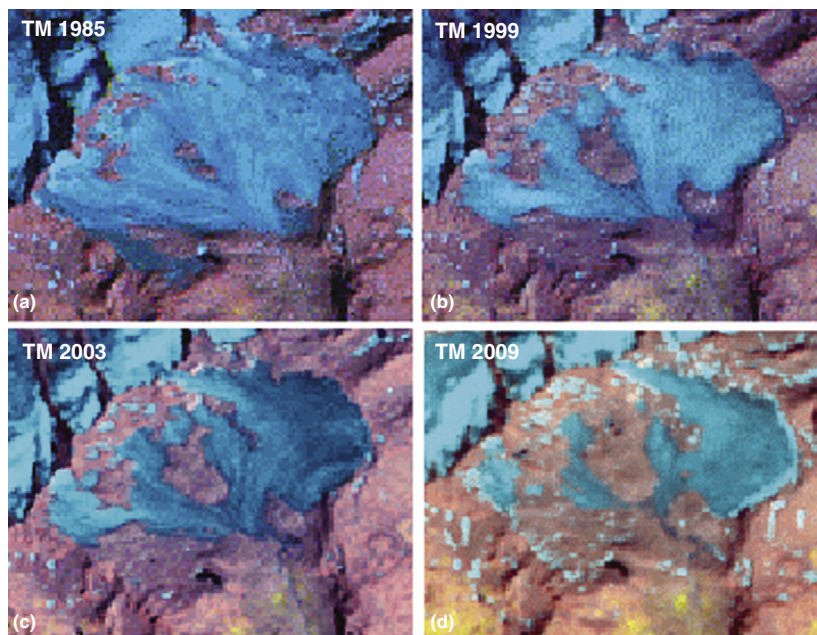
Figure 24 Time series of Landsat-TM images from the disintegrating Careser glacier (Italian Alps) – a long-observed important but now rapidly vanishing glacier in the worldwide glacier mass-balance network (false color composite with bands 5, 4, and 3 as RGB) acquired in (a) 1985, (b) 1999, (c) 2003, and (d) 2009.

replacements. Corresponding activities have to start now or at least very soon, because an overlapping time period with parallel measurements on the previous as well as on the new glaciers must be foreseen. A strategy for assessing suitable new glaciers should be based on field experience and local knowledge as well as on sensitivity modeling and scenario analyses. Important possibilities for corresponding analyses are provided by the combination of distributed energy/mass-balance modeling, which addresses ensembles of glaciers rather than being tuned to one single glacier only (cf. Machguth et al., 2006b, 2009), and which refer to information on changes of large regional glacier ensembles from DEM differencing (Paul and Haeberli, 2008). Not only the size of the new glaciers must be considered, but also their topographic and morphological characteristics. Neither a heavily debris-covered tongue, nor a tongue calving into an already existing/potentially forming larger lake or producing ice avalanches should be selected.

New technologies such as airborne laser altimetry in combination with kinematic GPS (Abdalati et al., 2004; Arendt et al., 2002; Geist et al., 2003), space-borne DEMs from SRTM, ASTER or SPOT (e.g., Berthier et al., 2004; Larsen et al., 2007; Rignot et al., 2003), and distributed mass and energy-balance modeling for large glacier ensembles (e.g., Machguth et al., 2006b) lead to new dimensions for glacier monitoring. Digital terrain information opens fascinating new possibilities of treating large numbers of glaciers. In fact, differencing the SRTM DEM (Rabus et al., 2003) with regionally available DEMs from earlier aerial photography started to provide quantitative information on volume/mass changes during the past decades for hundreds and thousands of large and small glaciers as well as on their individual parts (Haeberli et al., 2007; Larsen et al., 2007; Schiefer et al., 2007; Paul and Haeberli, 2008; Surazakov and Aizen, 2006). For the first time, it is now possible to directly investigate how representative the thickness changes of the glaciers in the mass-balance observation network are in comparison with all glaciers of entire mountain chains (Paul and Haeberli, 2008); what the variability in space is; and how it depends on factors such as size, slope, exposure, altitudinal extent or (micro-) climatic conditions of individual glaciers. Relative differences between long-term volume/mass changes of individual glaciers can be turned into correction factors for fitting mass-balance time series with transitions from replaced to replacing glaciers. Distributed energy- and mass-balance models may also be used to better understand corresponding patterns and relations (Arnold et al., 2006; Machguth et al., 2008).

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Biographical Sketch

Wilfried Haeberli is full professor at the Geography Department, University of Zurich, Switzerland. His research focuses on glaciology, geomorphodynamics, and geochronology. From 1989 to 1995, he led the Glaciology Section at the Laboratory of Hydraulics, Hydrology, and Glaciology of ETH Zurich, from 1986 to 2010 he was the director of the World Glacier Monitoring Service (WGMS) of IACS/ICSU, UNEP, UNESCO, and WMO and from 1998 to 2003 he served as a vice president of the International Permafrost Association (IPA). As a member of the Terrestrial Observation Panel for Climate (TOP-C) from 1996 to 2009 he was responsible for the integration of the cryosphere components as Essential Climate Variables into the terrestrial part (Global Terrestrial Observing System; GTOS) of the Global Climate Observing System (GCOS). He has been actively involved in various functions with IPCC assessments from the very beginning and works as an expert and consultant concerning high-mountain hazards in various countries of South America, Asia, and Europe.

Christian Huggel has a PhD in physical geography. He is a senior scientist at the University of Zürich and at the University of Geneva, Switzerland. For the Intergovernmental Panel on Climate Change (IPCC), he acts as an expert concerning extreme events in high-mountain regions and as a lead author in Working Group II of the Fifth Assessment Report. His research interests are in climate change impacts in high mountains, associated hazards and risks, as well as adaptation and prevention thereof with practical field experience as a consultant in Asia, Europe, and South America.

Frank Paul has a diploma in meteorology from the University of Hamburg and a PhD in physical geography from the University of Zurich, where he is currently working as a senior research scientist. His research interests cover glacier mapping and monitoring from space-borne optical sensors, distributed mass-balance modeling of glaciers, and geomorphometric analysis of DEMs and their applications in glaciological studies. He leads important projects (GlobGlacier, CCI-Glaciers) of the European Space Agency (ESA) concerning satellite-based glacier monitoring and acts as a lead author in Working Group I for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

Michael Zemp has a PhD in physical geography. He is a senior scientist at the Department of Geography of the University of Zurich, Switzerland and since 2010 the acting director of the World Glacier Monitoring Service. His main research interests are in earth observation technologies and geo-informatics and their application to the investigation of climate–glacier interactions. Over the past years the main focus of his work related to the structuring and management of worldwide glacier monitoring within internationally coordinated UN-related climate programs (Global Climate Observing System) and to the analysis of the resulting data base, especially with respect to current acceleration trends and in view to possible future developments.