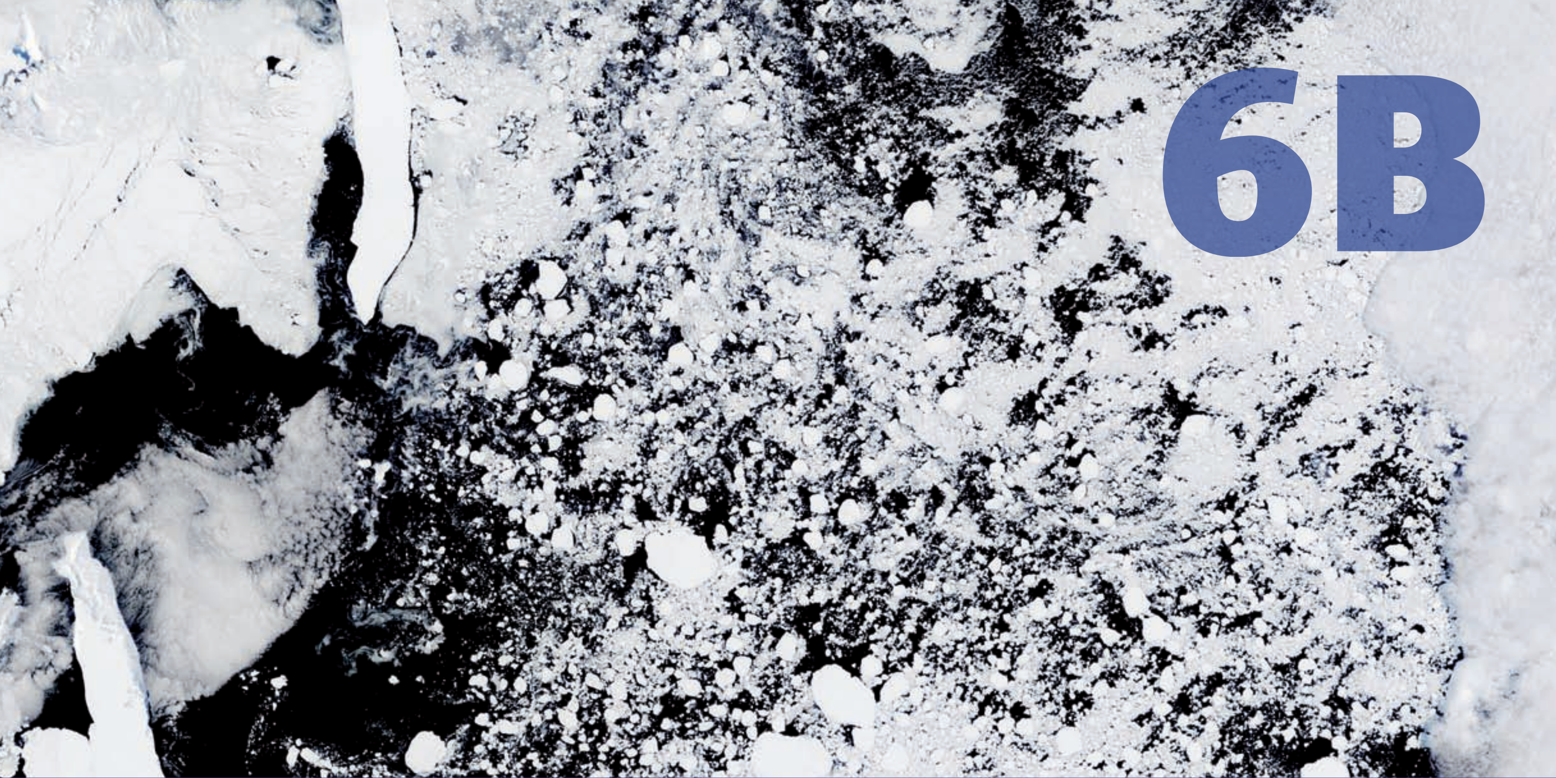


6B

Glaciers and Ice Caps

Michael Zemp (lead author, Department of Geography, University of Zurich, Switzerland); **Wilfried Haeberli** (lead author, Department of Geography, University of Zurich, Switzerland)

Contributing Authors for Regional Perspectives and Glacier Hazards:
Samjwal Bajracharya *Himalayas* (International Centre for Integrated Mountain Development, Nepal); **Trevor J. Chinn** *New Zealand* (Alpine and Polar Processes, New Zealand); **Andrew G. Fountain** *USA and Canada* (Department of Geology, Portland State University, USA); **Jon Ove Hagen** *Norway* (Department of Geosciences, University of Oslo, Norway); **Christian Huggel** *Glaciers and hazards* (Department of Geography, University of Zurich, Switzerland); **Andreas Kääb** *Glaciers and hazards* (Department of Geosciences, University of Oslo, Norway); **Bjørn P. Kaltenborn** *Himalayas* (Norwegian Institute for Nature Research, Lillehammer, Norway); **Madhav Karki** *Himalayas* (International Centre for Integrated Mountain Development, Nepal); **Georg Kaser** *Tropics* (Institute of Geography, University of Innsbruck, Austria); **Vladimir M. Kotlyakov** *Russian Territory* (Institute of Geography, Moscow State University, Russia); **Christian Lambrechts** *Africa* (Division of Early Warning and Assessment, United Nations Environment Programme, Kenya); **Zhongqin Li** *China* (Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, China); **Bruce F. Molnia** *Alaska* (U.S. Geological Survey, USA); **Pradeep Mool** *Himalayas* (International Centre for Integrated Mountain Development, Nepal); **Christian Nellemann** *Himalayas* (UNEP/GRID-Arendal, Arendal, Norway); **Viktor Novikov** *Central Asia* (UNEP/GRID-Arendal, Arendal, Norway); **Galina B. Osipova** *Russian Territory* (Institute of Geography, Moscow State University, Russia); **Andrés Rivera** *South America* (Centro de Estudios Científicos, Chile); **Basanta Shrestha** *Himalayas* (International Centre for Integrated Mountain Development, Nepal); **Felix Svoboda** *Baffin Island* (Department of Geography, University of Zurich, Switzerland); **Dmitri G. Tsvetkov** *Russian Territory* (Institute of Geography, Moscow State University, Russia); and **Tandong Yao** *China* (Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, China)

Glaciers and Ice Caps

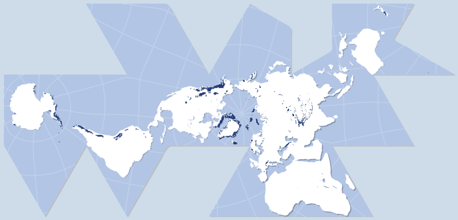
Summary

Glaciers and ice caps are among the most fascinating elements of nature, an important freshwater resource but also a potential cause of serious natural hazards. Because they are close to the melting point and react strongly to climate change, glaciers are important indicators of global climate.

Glaciers reached their Holocene (the past 10 000 years) maximum extent towards the end of the Little Ice Age (the Little Ice Age extended from the early 14th to mid-19th century.) Since then, glaciers around the globe have been shrinking dramatically, with increasing rates of ice loss since the mid-1980s. On a time-scale of decades, glaciers in various mountain ranges have shown intermittent re-advances. However, under the present climate scenarios, the ongoing trend of worldwide and fast, if not accelerating, glacier shrinkage on the century time-scale is not a periodic change and may lead to the deglaciation of many mountain regions by the end of the 21st century.

Glacial retreat and melting of permafrost will shift cryospheric hazard zones. This, in combination with the increasing socio-economic development in mountain regions, will most probably lead to hazard conditions beyond historical precedence. Changes in glaciers may strongly affect the seasonal availability of freshwater, especially when the reduction of glacier runoff occurs in combination with reduced snow cover in winter and earlier snowmelt, less summer precipitation, and enhanced evaporation due to warmer temperatures. The most critical regions will be those where large populations depend mainly on water resources from glaciers during the dry season and glaciated mountain ranges that are densely populated and highly developed.

This chapter on glaciers and ice caps is divided into two parts: 1) Global Overview and Outlook, and 2) Glacier Changes around the World.



Glacier: a mass of surface-ice on land 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 discharge into the sea.
Ice cap: dome-shaped glacier with radial flow, usually covering a highland area. Much smaller than an ice sheet.

Glaciers and ice caps (lowest and [highest] estimates):

Area Covered (million square km)	0.51 [0.54]
Ice Volume (million cubic km)	0.05 [0.13]
Potential Sea Level Rise (cm)	15 [37]

Source: IPCC 2007[1]

Part One: Global Overview and Outlook

Introduction to glaciers and ice caps

Glaciers and ice caps form around the world where snow deposited during the cold/humid season does not entirely melt during warm/dry times. This seasonal snow gradually becomes denser and transforms into perennial firn (rounded, well-bonded snow that is older than one year) and finally, after the air passages connecting the grains are closed off, into ice[2]. The ice from such accumulation areas then flows under the influence of its own weight and the local slopes down to lower altitudes, where it melts again (ablation areas). Accumulation and ablation areas are separated by an equilibrium line, where the balance between gain and loss in the ice mass is exactly zero. Where glaciers form thus depends not only on air temperature and precipitation (see Figure 6B.1), but also on the terrain, which determines how much solar radiation the glacier will receive and where ice and snow will accumulate.

In humid-maritime climates the equilibrium line is at a relatively low altitude because, for ablation to take place, warm temperatures and long melting seasons are needed to melt the thick layers of snow that accumulate each year[3,4]. These landscapes are thus dominated by 'temperate' glaciers with firn and ice at melting temperatures. Temperate glaciers have a relatively rapid flow, exhibit a high mass turnover and react strongly to atmospheric warming by enhanced melt and runoff. The ice caps and valley glaciers of Patagonia and Iceland, the western Cordillera of North America, and the mountains of New Zealand and Norway are examples of this type of glacier (Figure 6B.2). The lower parts of such temperate glaciers may extend into forested valleys, where summer warmth and winter snow accumulation prevent development of permafrost.

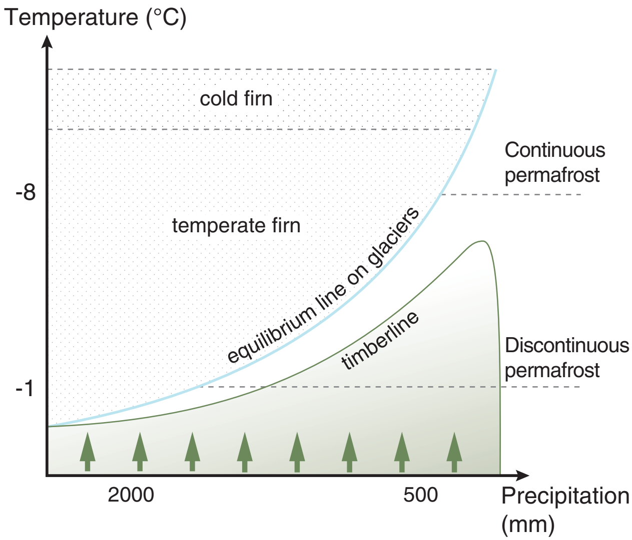


Figure 6B.1: Schematic diagram of glacier, permafrost and forest limits as a function of mean annual air temperature and average annual precipitation. Forests verge on glaciers in humid-maritime climates and grow above permafrost in dry-continental areas.

Source: Based on Shumsky 1964[3] and Haeberli and Burn 2002[4]

In dry continental areas, on the other hand, such as northern Alaska, Arctic Canada, subarctic Russia, parts of the Andes near the Atacama Desert, and many central-Asian mountain chains (Figure 6B.3), the equilibrium line is at a relatively high elevation with cold temperatures and short melting seasons. In such regions, glaciers far above the tree line can contain – or even consist entirely of – cold firn and ice well below melting temperature. These glaciers have a low mass turnover and are often surrounded by permafrost[3].

Glacier responses to climatic changes

The response of a glacier to climatic change involves a complex chain of processes[5,6]. Changes in atmospheric conditions (such as solar radiation, air temperature, precipitation, wind and cloudiness) influence the mass and energy balance at the glacier surface[7,8]. Air temperature plays a predominant role, as it is related to the radiation balance and turbulent heat exchange, and it determines whether precipitation falls as snow or rain. Over time periods of years and decades, changes in energy and mass balance cause changes in volume and thickness, which in turn affect the flow of ice through internal deformation and basal sliding.

This dynamic reaction eventually leads to changes in the length of the glacier – the advance or retreat of glacier tongues. In short, the glacier mass balance (the change in vertical thickness) is the direct signal of annual atmospheric conditions – with no delay – whereas the advance or retreat of glacier tongues (the change in horizontal length) is an indirect, delayed and filtered signal of climat-

Figure 6B.2: Franz Josef Glacier, New Zealand. This temperate glacier receives several metres of precipitation a year and its tongue extends from almost 3 000 m above sea level down to 400 m above sea level, ending in the rainforest.
Photo: Michael Hambrey, SwissEduc (www.swisseduc.ch) and Glaciers online (www.glaciers-online.net); data from the World Glacier Monitoring Service, Zurich, Switzerland

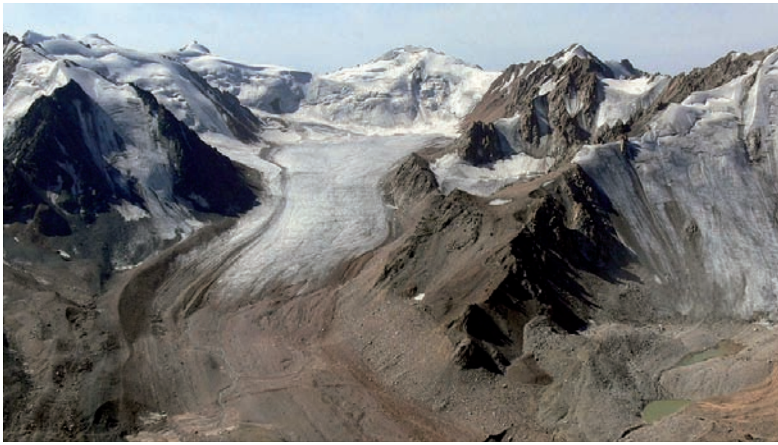


Figure 6B.3: Tsentralniy Tuyuksuyskiy Glacier, Kazhak Tien Shan in August 2006. This cold to partly temperate glacier extends from 4200 m above sea level to about 3400 m above sea level and is surrounded by continuous permafrost.
Photo: V.N. Vinokhodov; data from the World Glacier Monitoring Service, Zurich, Switzerland

ic change[9]. The advance or retreat of a glacier is, though, an easily-observed and strong signal of climatic change, as long as it is observed over a long enough period. If the time interval of the analysis is longer than the time it takes a glacier to adjust to a change in climate, the complications involved with the dynamic response disappear[10,11].

Over time periods of decades, cumulative length and mass change can be directly compared. Special problems are encountered with heavily debris-covered glaciers with reduced melting and strongly limited 'retreat', glaciers that end in deep-water bodies causing enhanced melting and calving, and glaciers undergoing periodic mechanical instability and rapid advance ('surges') after extended periods of stagnation and recovery. But glaciers that are not influenced by these special problems are recognized to be among the best indicators of global climate change[12,20]. They essentially convert a small change in climate, such as a temperature change of 0.1°C per decade over a longer time period, into a pronounced length change of several hundred metres or even kilometres (Figure 6B.4) – a signal that is visible and easily understood.

Past glacier fluctuations and current trends

The Late Glacial and Holocene (the period since about 21 000 years ago)

At the time of the peak of the last ice age about 21 000 years ago, glaciers covered up to 30 per cent of the land[2]. Glacier fluctuations can be reconstructed back to that time using a variety of scientific methods. Understand-

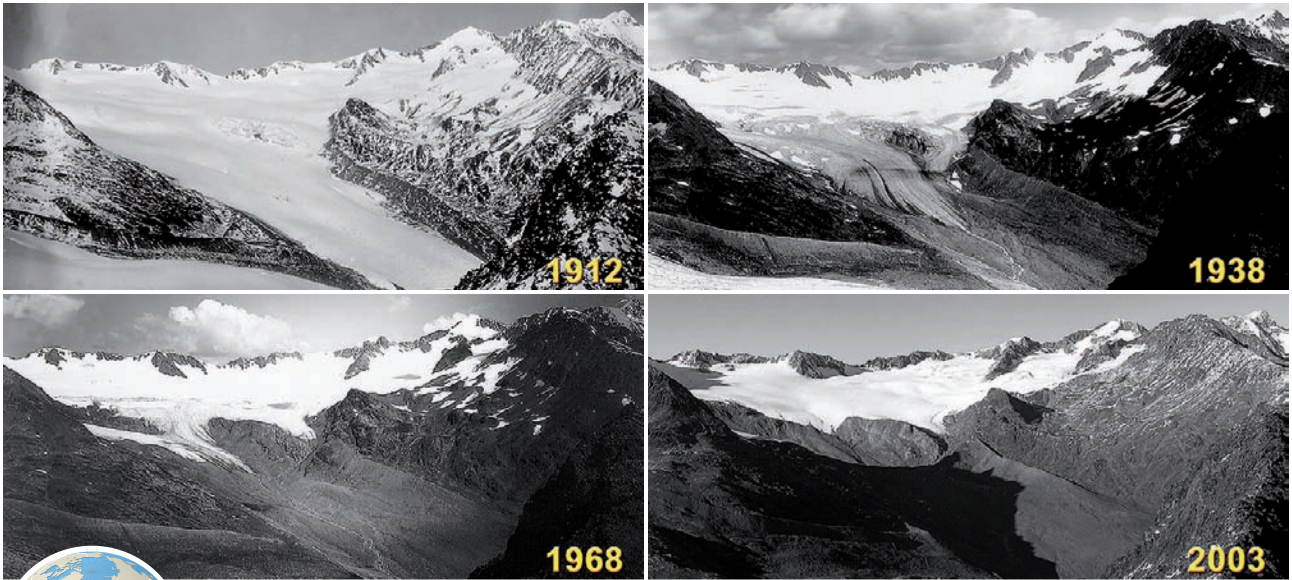


Figure 6B.4: Shrinking of Vernagtferner, Austria. This glacier in the European Alps lost almost 30% in area and more than 50% in mass between 1912 and 2003.

Source: Data and photos, taken by O. Gruber (1912), H. Schatz (1938), H. Rentsch (1968) and M. Siebers (2003), provided by the Commission for Glaciology of the Bavarian Academy of Sciences and Humanities (www.glaziologie.de) ing how glaciers have varied in the past has become central to understanding the causes and possible future of contemporary glacier change. Historical reconstruction of glaciers in the Alps, Scandinavia, Alaska, the Canadian Rockies, Patagonia, the Tropics of South America, Tibet, the Arctic and Antarctica shows that the fluctuations in the state of the glaciers are largely consistent with the reconstruction of climatic and environmental changes provided by other indicators, such as ice-cores, tree-line shifts, pollen records and lake sediments[14].

General warming during the transition from the Late Glacial period (between the Last Glacial Maximum and about 10 000 years ago) to the early Holocene (about 10 000 to 6000 years ago) led to a drastic general glacier retreat with intermittent periods of re-advances. About 11 000 to 10 000 years ago, this pronounced warming reduced the glaciers in most mountain areas to sizes comparable with conditions at the end of the 20th century[15]. In northern Europe and western North America, which were still influenced by the remnants of the great ice sheets, this process was delayed until about 6000 to 4000 years ago. Several early-Holocene re-advances, especially those in the North Atlantic and North Pacific as well as possibly in the Alps, cluster around an event about 8000 years ago, and were likely triggered by changes in the ocean thermohaline circulation and subsequent cooling resulting from the outbursts of Lake Agassiz[14].

On a timescale of hundreds of years there were periods of synchronous glacier advance around the world – peaking in the late Holocene in the Northern Hemisphere, and in the early Holocene in the Southern Hemisphere[16]. The difference in the amount of sunlight that reaches the Earth's surface in the two hemispheres[17], accounts for these differences in long-term glacier evolution[16]. Glaciers in the tropics were rather small or even absent in the early- to mid-Holocene, gradually re-advancing from about 4 000 years ago, probably as a result of increasing humidity[18]. The moraines (accumulations of unsorted, unstratified mixtures of clay, silt, sand, gravel, and boulders deposited by the glaciers) that were formed during the so-called Little Ice Age (from the early 14th to the mid 19th centuries) mark a Holocene maximum extent of glaciers in many regions of the world, although the time period for this maximum varies among the different regions.

There is evidence that mountain glaciers had retreated during various periods of the Holocene in many regions of both hemispheres at least as much as they had in the 1980s–1990s[14]. However, caution must be exercised when using glacier extent as an indicator of climate; the glacier surfaces of the European Alps today, for example, are still far larger than expected given the climatic conditions of the past decade, and are thus not in equilibrium[19].

Since the end of the Little Ice Age

There has been a general retreat of glaciers worldwide 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 intermittent periods of glacier re-advance in certain regions. Direct measurements of glacier fluctuations started in the late 19th century (see box on worldwide glacier monitoring) with annual observations of glacier front variations[20]. These observations and the positions of the Little Ice Age moraines are used to measure the extent of glacier retreat. Total retreat over this time period of glacier termini (the ends of the glaciers) is commonly measured in kilometres for larger glaciers and in hundreds of metres for smaller ones[21].

Worldwide glacier monitoring

Worldwide 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. Today, the World Glacier Monitoring Service continues to collect and publish standardized information on ongoing glacier changes. WGMS is a service of the Commission for the Cryospheric Sciences of the International Union of Geodesy and Geophysics (CCS/IUGG) and maintains a network of local investigators and national correspondents in all the countries involved in glacier monitoring. In addition, the WGMS is in charge of the Global Terrestrial Network for Glaciers (GTN-G) within the Global Climate/Terrestrial Observing System. GTN-G aims at combining (a) in-situ observations with remotely sensed data, (b) process understanding with global coverage and (c) traditional measurements with new technologies by using an integrated and multi-level strategy[20]. Recently, a scientific working group has been established to coordinate the monitoring and assessment of glacier and permafrost hazards in mountains[22].

To keep track of the fast changes in nature and to assess corresponding impacts on landscape evolution, fresh water supply and natural hazards, monitoring strategies will have to make use of the rapidly developing new technologies (remote sensing and geo-informatics) and relate them to the more traditional methods.

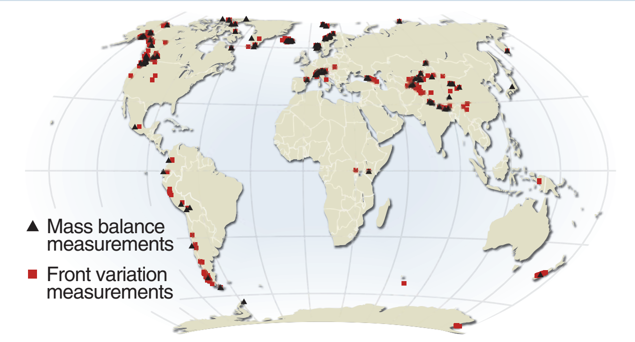


Figure 6B.5: Worldwide glacier monitoring. The locations of glaciers with available front variation and mass balance measurements are shown.

Source: Locations of glacier observations provided by the World Glacier Monitoring Service, Zurich, Switzerland; background glacier cover based on the glacier layer of the Digital Chart of the World, provided by the National Snow and Ice Data Center, Boulder, USA.

Characteristic average rates of glacier thinning (mass loss), calculated from data on changes in length over long time periods, are a few decimetres water equivalent per year for temperate glaciers in humid-maritime climates, and between a few centimetres and one decimetre water equivalent per year for glaciers in dry-continental regions with firn areas below melting temperature[21,23]. These calculated values of glacier mass loss can be compared to glacier mass balance values from direct glaciological measurements, which are available for the second half of the 20th century.

Thirty reference glaciers with almost continuous mass balance measurements since 1975 (Figure 6B.6) show an average annual mass loss of 0.58 m water equivalent for the past decade (1996–2005), which is more than twice the loss rate of the period 1986–1995 (0.25 m), and more than four times the rate of the period 1976–1985 (0.14 m). The results from these 30 continuous mass balance series correspond well to estimates based on a larger sample of more than 300 glaciers, including short and discontinuous series[24].

The mass loss of glaciers and ice caps (excluding peripheral ice bodies around the two ice sheets in Greenland and Antarctica) between 1961 and 1990 contributed 0.33 mm per year to the rising sea level, with about a doubling of this rate in the period from 1991 to 2004[24]. A step-change in climatic conditions would cause an initial mass balance change followed by a return towards zero values, due to the glacier's adaptation of its size (surface area) to the new climate. The observed trend of increasingly negative mass balances over reducing glacier surface areas thus leaves no doubt about the ongoing change in climatic conditions.

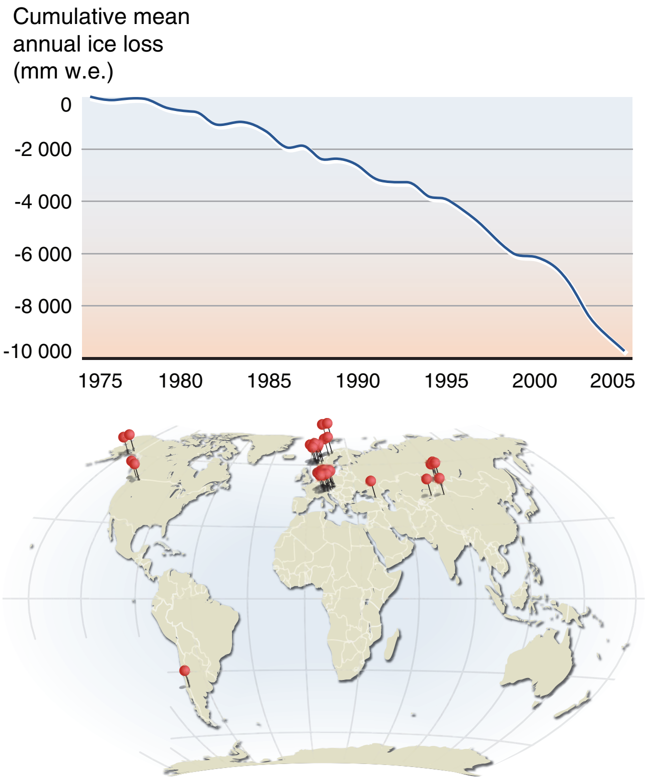


Figure 6B.6: Mass balance reference glaciers in nine mountain ranges. The 30 glaciers lost on average more than 9.5 m water equivalent in thickness over the period 1976–2005.

Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland

Outlook for glaciers

The total increase of global mean air temperature of about 0.75 °C since 1850 is clearly manifested in the shrinking of glaciers and ice caps worldwide[1]. The sensitivity of glaciers in humid-maritime areas to this warming trend has been found to be much higher than that of glaciers in dry-continental areas[7,21].

According to climate scenarios for the end of the 21st century, changes in global temperature and precipitation range between +1.1 to +6.4 °C and –30 to +30 per cent, respectively[1]. Such an increase in mean air temperature will continue the already dramatic glacier changes. Cold continental-type glaciers will react in the first instance with a warming of the ice and firn temperatures, whereas glaciers with ice temperatures at the melting point will have to convert the additional energy directly into melting[7,8].

Low-latitude mountain chains like the European Alps or the Southern Alps of New Zealand, where glaciers are typically medium-sized and found in quite steep mountains, will experience rapid glacier changes in adaptation to the modified climate. A modelling study shows that the European Alps would lose about 80 per cent of their glacier cover should summer air temperatures rise by 3°C, and that a precipitation increase of 25 per cent for each 1°C would be needed to offset the glacial loss[19].

In heavily glacier-covered regions like Patagonia (Argentina, Chile) or the St. Elias Mountains (Alaska), the landscape is dominated by relatively few large and rather flat valley glaciers. Because long, flat valley glaciers have dynamic response times beyond the century scale[10,11], rapid climate change primarily causes (vertical) thinning of ice rather than (horizontal) retreat and area reduction. For such cases, conditions far beyond equilibrium stages, perhaps even run-away effects from positive feedbacks (mass balance/altitude), must be envisaged[20,25]. Downwasting or even collapse of large ice bodies could become the most likely future scenarios related to accelerating atmospheric temperature rise in these areas, and have already been documented[26,27].

Under the present climate scenarios[1], the ongoing trend of worldwide and fast, if not accelerating, glacier shrinkage on the century time scale is of a non-periodical nature and may lead to the deglaciation of large parts of many mountain regions in the coming decades.

Glacier melt water in the Caucasus mountains, Georgia.
Photo: Igor Smichkov/iStockphoto.com

Glaciers and natural hazards

Changes in glaciers may well lead to hazardous conditions, particularly in the form of avalanches and floods, and thus have dramatic impacts on human populations and activities located in glacierized mountain regions. The majority of glacier hazards affect only a limited area – often only a few square kilometres – and mostly pose a danger to densely populated mountain regions such as the European Alps. In some cases, however, glacier hazards have far-reaching effects over tens or even hundreds of kilometres and thus also affect less densely populated and developed mountain regions. The long-term average annual economic loss from glacier disasters or related mitigations costs are estimated to be in the order of several hundred million US dollars[28]. The largest disasters have killed more than 20 000 people, for instance the Huascarán rock-ice avalanches in Peru in 1970 (see box on deadly ice avalanches of Glaciar 511 in the Cordillera Blanca in Part 2 of this chapter), or the Nevado del Ruiz lahars (rapidly flowing volcanic debris flows) in Colombia in 1985.

A systematic assessment of hazards can only be achieved by identifying the physical processes involved. Generally speaking, the most important types of hazards are as follows: glacier floods, hazardous processes associated with glacier advance or retreat, ice and rock avalanches, periglacial debris flows, and ice–volcano interactions[29,30]. Particularly severe disasters have often resulted from a combination of these processes or chain reactions[13,31].

Glacier lake outburst floods represent the largest and most extensive glacial hazard, that is, the hazard with the highest potential for disaster and damage (up to 100 million m^3 break-out volume and up to 10 000 m^3 per second runoff). The Himalayas, Tien Shan and the Pamirs (see box on glacier lake outburst floods and glacier surges in Central Asia), the Andes, but also the European Alps are among those regions most severely affected by this type of hazard. Glacier floods are of particular concern in view of the rapidly retreating glaciers and the corresponding formation and growth of numerous glacier lakes[30,32–34].

In terms of hazard, ice and rock avalanches may be roughly grouped by volume. Avalanches with volumes smaller than 1 million m^3 are mostly of concern to densely populated and developed mountain regions such as the European Alps[41–43]. Avalanches with a volume of 1 to 100 million m^3 or even more have usually more far reaching effects and the potential to completely devastate mountain valleys. The most recent such disaster occurred in 2002 in the Caucasus with a 100 million m^3 ice-rock avalanche that extended more than 30 km downstream and killed more than 100 people (see box on the 2002 Caucasus ice-rock avalanche and its implications). These types of mass movements and the relationship between their magnitude and their frequency have recently have become more and more important in research because of concerns that they may become more frequent with continuing atmospheric warming, permafrost degradation and related destabilization of steep glaciers and rock walls[44].

Debris flows from periglacial areas have frequently caused damage to life and property in mountain areas[48]. Unconsolidated sediments, uncovered by glacier retreat during the recent decades, and degradation of stabilizing permafrost in debris slopes are the main sources of the largest debris flows observed in the European Alps[31,49,50].

Ice-capped volcanoes pose particularly severe hazards because large mass movements (avalanches, lahars) may result from the interactions between material that erupts from the volcanoes with ice and snow[51,52]. Alaska, the Cascades and the Andes are among the regions most affected by hazards posed by the interaction between volcanoes and glaciers[53,54].

Chain reactions and interactions between the aforementioned processes play a crucial role in determining the

Glacier lake outburst floods and glacier surges in Central Asia

Almaty (population 1.2 million) is subject to the risk of floods from torrential rainfalls and glacial lake outbursts. A glacier-induced debris flow in July 1973 in the mountains south of Almaty deposited over 4 million m^3 of debris into the safety dam, which had been specially constructed to prevent the catastrophic impacts of such floods. Before this dam was built in 1967, debris flows caused many casualties and severe destruction in 1921 and 1956[35,36].

In July 1998, a glacier lake outburst flood in the Shahimardan Valley of Kyrgyzstan and Uzbekistan killed over 100 people[37]. In August 2002, another such event in the Shakhdara Valley of the Tajik Pamir Mountains claimed 23 lives[38]. In both cases the local communities did not receive early warnings and were not prepared. These tragic lessons have prompted better cooperation between meteorological services in glacier flood hazard detection.

The increasing number of glacial and moraine lakes in Central Asian mountains is a matter of great concern[35,39]. One of the surging glaciers that poses a potential threat is the 15 km long Medvezhi (Bear) Glacier in the Pamirs mountains of Tajikistan (Figure 6B.7). Its surges have repeatedly caused lake formation, outburst and subsequent floodings. In 1963 and 1973, the surge of the glacier was so significant (1 to 2 km increase in length) that the ice dam exceeded 100 m in height and dammed a lake of over 20 million m^3 of water and debris[40]. The outburst of that lake generated a series of large flood waves. Due to early warning and monitoring, there were no victims, although infrastructural damage was significant.

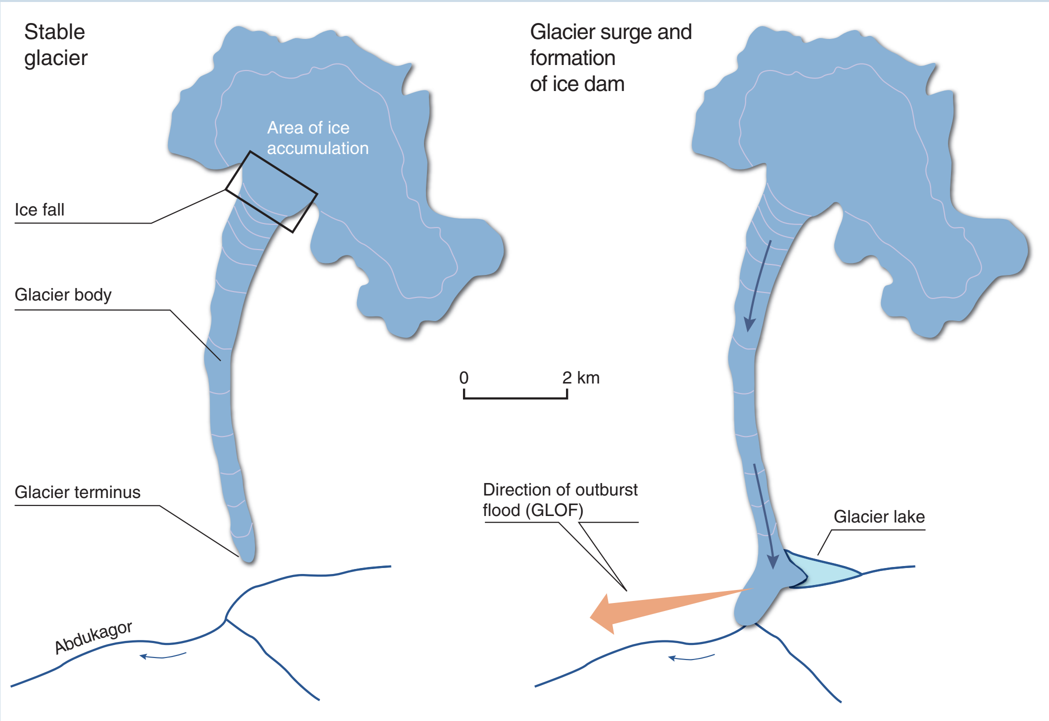


Figure 6B.7: Formation of lakes and glacier lake outburst floods (GLOFs) by Medvezhi Glacier, Pamirs.

Source: Tajik Agency on Hydrometerology

The 2002 Caucasus ice-rock avalanche and its implications

One of the largest historical glacier disasters occurred in 2002 in the Russian Republic of North Ossetia in the Caucasus. An ice-rock avalanche resulting from a slope failure in the Kazbek region and a connected instability of the Kolka glacier devastated tens of kilometres along the length of the Genaldon valley[13,45–47]. The Kolka ice-rock avalanche (Figure 6B.8) is remarkable for several reasons. The steep, high mountain wall of the initial slope failure was covered by firn and ice masses, a composition that is inherently unstable. The underlying bedrock in relatively cold permafrost conditions was influenced by deep-seated thermal anomalies induced by the overlying ice and firn through processes such as latent heat production from percolating and refreezing meltwater[13]. Increasing air temperatures can cause disturbances in such complex system, which eventually can lead to slope failure. Similar conditions as in the Caucasus exist in many glacierized mountain regions of the world. In more populated areas such as the European Alps, similarly large slope failures would cause catastrophes of even much larger dimensions.

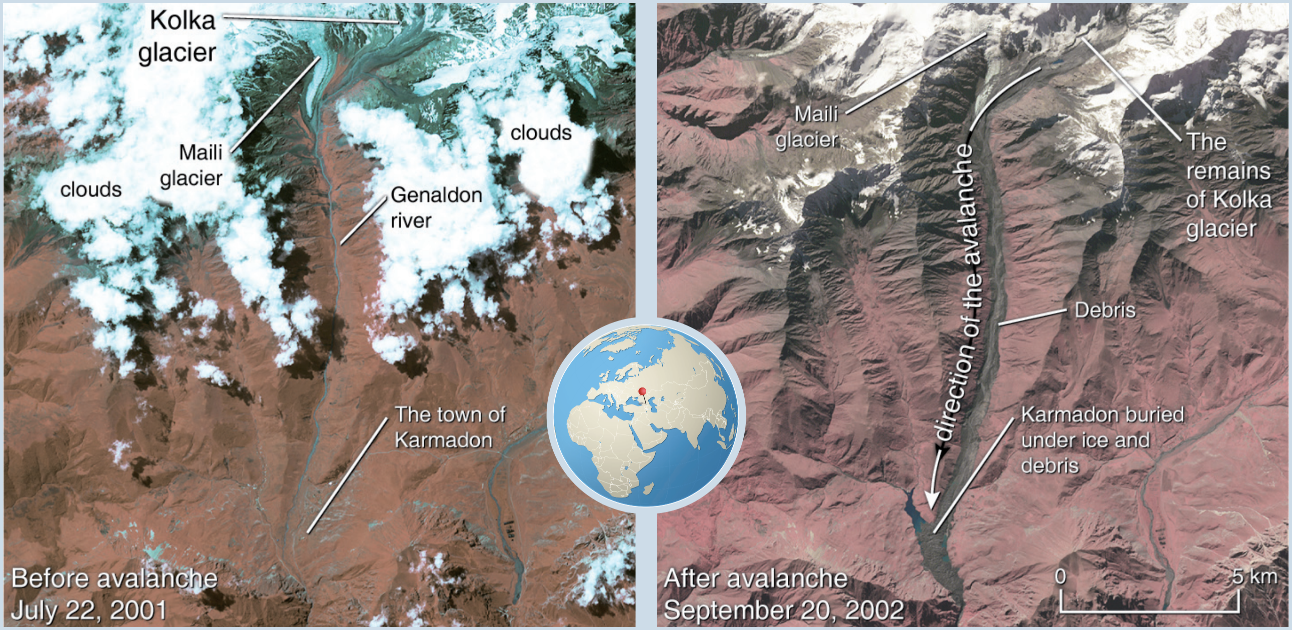


Figure 6B.8: Caucasus ice-rock avalanche in Russian Republic of North Ossetia. An ice-rock avalanche in the Kazbek region sheared off almost the entire Kolka Glacier and devastated the Genaldon valley. The satellite images show the region before (July 22, 2001) and after (October 6, 2002) the ice-rock avalanche of September 20, 2002.

Source: The ASTER scenes were provided within the framework of the Global Land Ice Measurements from Space project (GLIMS) through the EROS data center, and are courtesy of NASA/GSFC/METI/ERSDAC/JAROS and the US/Japan ASTER science team magnitude and frequency of glacier-related hazards. As one example, outbursts of naturally or artificially dammed mountain lakes were caused by impact waves from rock and ice avalanches and this led to failure of the dams[55]. Such potential process interactions have to be assessed carefully in order to predict related consequences.

Two present global developments and their regional expressions will strongly affect the potential impact of current and possible future glacier hazards: climate change and socio-economic development. First, atmospheric warming has an increasingly dramatic effect on mountain glaciers[1], and strongly influences the development of related hazards. For example, potentially unstable glacial lakes often form in glacier forefields dammed by frontal moraines which were left behind by retreating glaciers. Steep slopes of unconsolidated debris are a potential source for debris flows when they are no longer covered by glacier ice or cemented by ground ice. Fresh ice break-off zones may evolve in new places from glacier retreat, while existing danger zones may cease to be active. Atmospheric warming also affects permafrost thickness and distribution. The thickness of the active layer (that is, the layer above the permanently frozen ground that thaws during the summer) may increase, and the magnitude and frequency of rockfalls may increase or evolve at locations where such events were historically unknown. Lateral rockwalls can be destabilized by glacier retreat as a result of the stress changes induced. In general, climate change is expected to bring about a shift of the cryospheric hazard zones. It is difficult, however, to ascertain whether the frequency and/or magnitude of events have actually increased already as a consequence of recent warming trends. Nevertheless, events with no historical precedence do already occur and must also be faced in the future[29,56].

The second important change in glacier-related risks concerns the increasing economic development in most mountain regions. Human activity is increasingly encroaching upon areas prone to natural hazards. Related problems affect both developed and developing countries. The latter (such as in Central Asia, the Himalayas or the Andes), however, often lack resources for adequate hazard mitigation policies and measures. Cost-efficient, sound and robust methods are therefore needed to regularly monitor the rapid environment and land-use changes in high mountains and to identify the most vulnerable areas. This is equally important for developed countries in the European Alps. Expensive protective structures had to be built in the past to reduce the risk. Public funds increasingly struggle to keep pace with – and to ensure sufficient protection from – the rapid environmental changes and their consequences in mountain areas. Integrating climate change effects and robust process models into risk studies will help ensure that politics and planning can adapt to environmental conditions that change with increasingly high rates.

Glaciers, landscapes and the water cycle

Landscapes around many high-mountain regions but also in vast lowlands were moulded and sculpted by large ice bodies during the most recent part of Earth's history – the Ice Ages – over the last few million years[57,58]. The detection, in the first half of the 19th century, of corresponding traces from glacier erosion and of erratic boulders far from mountain chains led to the formulation of the Ice Age theory by Louis Agassiz and colleagues[59]. It was soon understood that large ice sheets had formed over North America and even entirely covered Scandinavia, lowering global sea level by more than 100 m, greatly modifying coastlines of all continents and dramatically affecting the courses of large rivers and the global ocean circulation[60,61]. This new knowledge constituted a fundamental breakthrough in our understanding of the climate system as an essential part of living conditions on Earth. Ice Age landforms have become a unique heritage, reminding us of the consequences of global temperature changes of just a few degrees.

Curiosity and romantic enthusiasm characterize many historical reports and paintings of glaciers and high mountain landscapes. Very often, glaciers are portrayed as an expression of 'wild, non-destroyable' nature, sharply contrasting with the cultivated landscape of human habitats. Glacierized mountain areas therefore became – and still are – major tourist attractions in many parts of the world. In fact, the 'clean white of the eternal snow' on high mountain peaks is often seen as a beautiful treasure and used as a precious symbol of intact environments[62]. This is why the current shrinking, decay and even complete vanishing of glaciers evokes such an emotional response.

Apart from their symbolic value, glaciers are also among the best natural indicators of climate change[12,20]. Their development can be observed by everybody – and the physical process, the melting of ice under the influence of warmer temperatures, can intuitively be understood. The impacts of accelerated atmospheric warming are thus changing the public perception of glaciers: they are increasingly recognized as a warning signal for the state of the climate system[63].

Continued atmospheric warming will inevitably lead to the deglaciation of many currently glacierized landscapes, especially in low-latitude mountain chains. In many places, lakes have already started to form. Such lakes may replace some of the lost landscape attractiveness, but their beauty may come at a dangerous price (as explained above in the section on natural hazards). On slopes, vegetation and soils take decades and even centuries or sometimes millennia to follow the retreating ice and cover the newly exposed terrain[64]. As a consequence, the zones of bare rock and loose debris will expand. Vegetation (especially forests) and ice both have a stabilizing effect on steeply inclined surfaces. During the expected long transitional period between glacier vanishing and forest immigration, erosion (including large debris flows) and instability (including large rockfalls and landslides) on slopes unprotected by ice or forest will increase substantially[65].

The perennial ice of glaciers is an important part of the water cycle in cold regions. It represents a storage component with strong effects on river discharge and fresh water supply[66,67]. Such effects indeed make high mountain chains 'water towers' for many large areas and human habitats. Climatic change will lead to pronounced changes in this system[12]. At time scales of tens and hundreds of millennia, the growth and decay of continental ice sheets, large ice caps and glaciers during periodical ice ages profoundly affect the global water cycle[61,68]. Within annual cycles of temperature and precipitation, glacial meltwater feeds rivers during the warm/dry season. In the Andes of Peru, the Argentinean Pampas or the Ganzhou Corridor of China, this contribution to river flow is the predominant source of freshwater for large regions surrounding the corresponding mountain areas[69]. Meltwater from glacierized mountain chains with rugged topography is also intensively used for hydropower generation (Figure 6B.9).

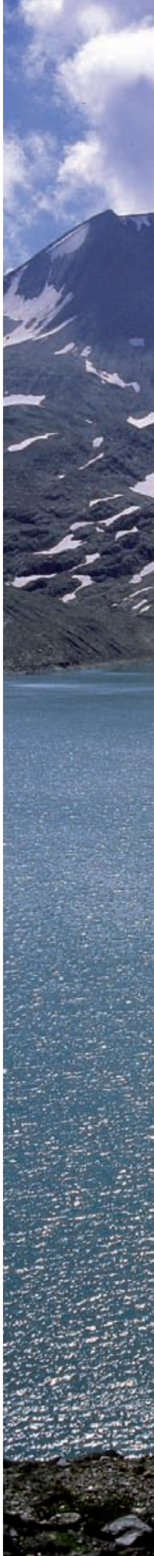


Figure 6B.9: Glaciers as source for hydropower production. A dam at Gries Glacier in Switzerland has been constructed to receive meltwater in summer for use in power generation in winter. *Photo: Jürg Alean, SwissEduc (www.swisseduc.ch)/Glaciers online (www.glaciers-online.net)*

The shrinking and even vanishing of mountain glaciers in scenarios of atmospheric temperature rise is likely to cause both small and large meltwater streams to dry out during hot and dry summers. This drying out may become more frequent at mid-latitudes, where human populations are often dense and the need for fresh water is growing. Earlier snowmelt and perhaps also reduced snow cover from wintertime could result in severe consequences for both ecosystems and related human needs: decreasing river flow, warmer water temperatures, critical conditions for fish and other aquatic forms of life, lower groundwater levels, less soil humidity, drier vegetation, more frequent forest fires, stronger needs for irrigation water, and rising demands for energy (such as air conditioning) coupled with reduced hydropower generation and less river cooling for nuclear power plants. These consequences are all likely to be interconnected and related to growing conflicts of interest.

Perhaps the most critical regions will be those where large populations depend on water from glaciers during the dry season, such as in China and other parts of Asia, including India, together forming the Himalaya-Hindu Kush region (see box on the water towers of Asia), or in the South American Andes[70] (see box on glaciers and water availability in the Andes, in Part 2 of this chapter). But it will also affect mountain ranges which are densely populated and highly developed, such as the European Alps and the regions in the vicinity of its rivers[71,72]. Glacier changes, as important and pronounced parts of climate-induced changes in mountain landscapes, are not only the clearest indication of climate change – they also have the potential of having a strong impact on the seasonal availability of fresh water for large, densely populated regions and, hence, on the fundamental basis of ecosystem stability and economic development[56,73].

The water towers of Asia

The Himalayas–Hindu Kush, Kunlun Shan, Pamir and Tien Shan mountain ranges (Figure 6B.10) function as water towers, providing water to people through much of Asia. The glacier-fed rivers originating from the mountain ranges surrounding the Tibetan Plateau comprise the largest river run-off from any single location in the world[74,75]. While the mountains are homes to some 170 million people, the rivers that drain these mountains influence the lives of about 40 per cent of the world's population[74]. The rivers provide household water, food, fisheries, power, jobs and are at the heart of cultural traditions. The rivers shape the landscape and ecosystems and are important in terms of biodiversity.

While mountains traditionally have been considered the major water sources of the region, there is great diversity in the hydrological significance of mountains and glaciers for downstream water supply, particularly between the dry north-western region and the monsoon-influenced south-eastern regions[76]. In spite of the vast water supply, seasonal water scarcity is a major issue[77].

Projections of glacier retreat in the region (based on IPCC scenarios) suggest that increases in the mean annual temperature for High Asia in the range of 1.0°C to 6.0°C (low to high estimate) by 2100 are likely to result in a decline in the current coverage of glaciers by 43 to 81 per cent[78]. The Tien Shan and Qinling Shan are likely to become entirely devoid of glaciers, and glacial cover-

Figure 6B.10: The Himalayas-Hindu Kush-Tien Shan-Tibet region.

age would be greatly diminished in the Himalayas–Hindu Kush[78]. The extent and amount of snow will also decrease as temperatures increase and the snow line moves to higher elevations. Given that some of the rivers, such as the Amu Darya and the Indus, receive nearly 90 per cent of their total water discharge from upper mountain catchments including glaciers and snow[76], the water flow in the rivers could decline perhaps by as much as 70 per cent if the glaciers disappear. In some cases, like in the Tien Shan, the rivers could become seasonal. Reduced water flow in the dry seasons will lead to more and longer periods with critical shortages of water for transportation, drinking water and irrigation, with consequences for trade, small and large-scale agriculture[74] and with increased potential for disputes over sectoral and regional allocations of this diminishing resource.

The impacts are not evenly distributed geographically or socially. High proportions of impoverished populations in the region are mountain and foothill dwellers[74,79,80]. Impoverished populations have also largely settled in areas with high flood risk, such as low-lying urban areas and deltas – because there is often no alternative[74]. The impacts are aggravated by the methods of meeting energy demands – traditional fuel sources such as fuel wood and animal dung account for 94 per cent of energy supply in some mountain areas in Nepal and Tibet[79]. Because of this dependence on fuel wood and livestock, most watersheds have experienced deforestation and overgrazing, making the hillsides much more vulnerable to land slides, either during peak snowmelt or in relation to tectonic activity[75]. Only 3 per cent of watersheds in the region are protected. High in the mountains, a rise in elevation of the snowline will lead to drying out of village grazing areas, eroding the basis of villagers' livelihoods by reducing the carrying capacity of their surrounding lands. Even slight increases in severity and frequency of land slides and flash floods may significantly reduce the ability of herders to move and transport their livestock between grazing areas and to towns for sale.

The hydrological role of mountains, glaciers and snow is particularly significant for the Tarim, Syr Darya, Amu Darya, Indus, Ganges, Brahmaputra, Yangtze and Huang He (Yellow) rivers[74,76,81] (Table 1). With increases in seasonal floods and significantly reduced overall water flow, especially during critical times of low rainfall, about 1.3 billion people could be exposed to risk of increased water shortages:

- in China up to 516 million people;
- in India and Bangladesh approximately 526 million people;
- in central Asia, including the Xinjiang province of China, about 49 million people;
- in Northern India and Pakistan as many as 178 million people.

This only includes the populations living in the watersheds, not those affected by reduced crop production from failure to secure water for irrigation, or those affected more generally from impacts on regional and national economies[82]. The result of glacier loss is therefore not only direct threats to lives, but also great risks of increased poverty, reduced trade and economic decline. This poses major political, environmental and social challenge in the coming decades.

River	Basin km^2	Total population	% cropland	% forest	% basin protected	Hydrological significance of glaciers and snow for rivers
Tarim	1 152 000	8 067 000	2	<1	21	Very high
Syr Darya	763 000	20 591 000	22	2.4	1.0	Very high
Amu Darya	535 000	20 855 000	22	0.1	0.7	Very high
Indus	1 082 000	178 483 000	30	0.4	4.4	Very high
Ganges	1 016 000	407 466 000	72	4.2	5.6	High
Brahmaputra	651 000	118 543 000	29	19	3.7	High
Yangtze	1 722 000	368 549 000	48	6.3	1.7	High
Huang He (Yellow river)	945 000	147 415 000	30	1.5	1.3	High
Salween	272 000	5 982 000	6	43	2.2	Moderate
Mekong	806 000	57 198 000	38	42	5.4	Moderate

Table 1: An overview of the major rivers in the Himalayas-Hindu Kush-Tien Shan-Tibet region.

Source: Viviroli and others 2003[76]; IUCN/WRI 2003[81]; UNEP 2004[74]

Part Two: Glacier Changes around the World

Overview

Glaciers and ice caps reached their Holocene (the past 10 000 years) maximum extent in most mountain ranges throughout the world towards the end of the Little Ice Age, between the 17th and mid-19th century. Over the past hundred years a trend of dramatic shrinking is apparent over the entire globe, especially at lower elevations and latitudes. Within this general trend, strong glacier retreat is observed in the 1930s and 1940s, followed by static conditions around the 1970s and by increasing rates of glacier wasting after the mid 1980s (Figure 6B.11). There are short-term regional deviations from this general trend and intermittent re-advances of glaciers in various mountain ranges occurred at different times.

The trend of worldwide glacier shrinking since the end of the Little Ice Age is consistent with the increase in global mean air temperature. The decline in solar radiation at the Earth's surface (global dimming) in the second half of the 20th century and the transition from decreasing to increasing solar radiation in the late 1980s may be due to the industrial pollution of the atmosphere and the more effective clean-air regulations together with the decline in the economy in Eastern European countries, respectively[83]. This might explain some of the glacier mass gains around the 1970s and the subsequent strong mass losses[84]. Significantly increased precipitation has been linked to the advance of glaciers on the west coast of New Zealand and Norway in the 1990s[85–87] and can give valuable insight into regional climate oscillations such as the El Niño/Southern Oscillation or the North Atlantic Oscillation[86,87].

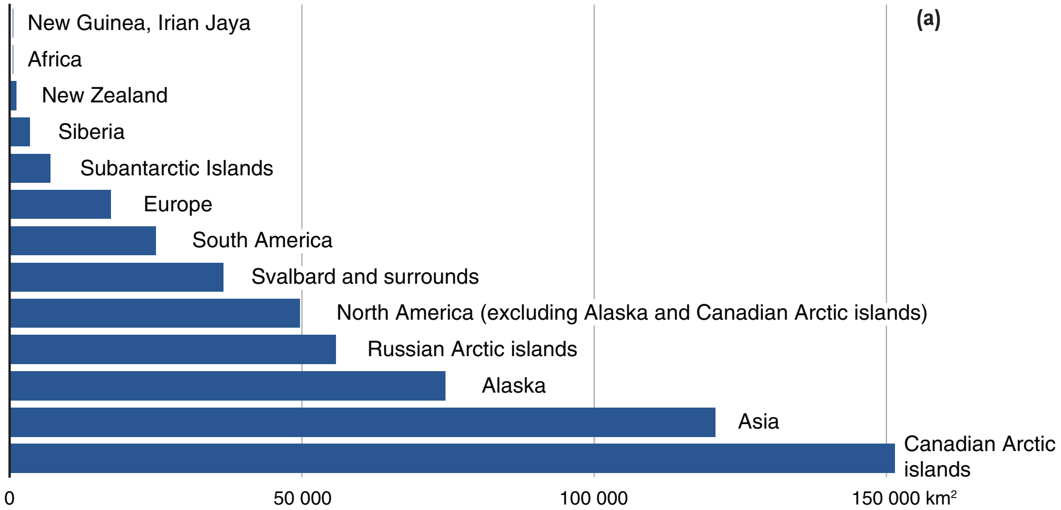
Glaciers act as vital water reservoirs maintaining river flows in many dry parts of the world. Increased melting of glaciers is providing increased flows in some areas but as glaciers continue to shrink and disappear the reservoirs will run dry, resulting in drought and hardship for many millions of people in and around regions such as the Andes, China, Central and Southern Asia, Iran and Afghanistan[70]. Increased glacial melting also results in heightened risk of flooding due to the failure and catastrophic discharge of unstable ice and detritus dams formed at the toe of receding glaciers.

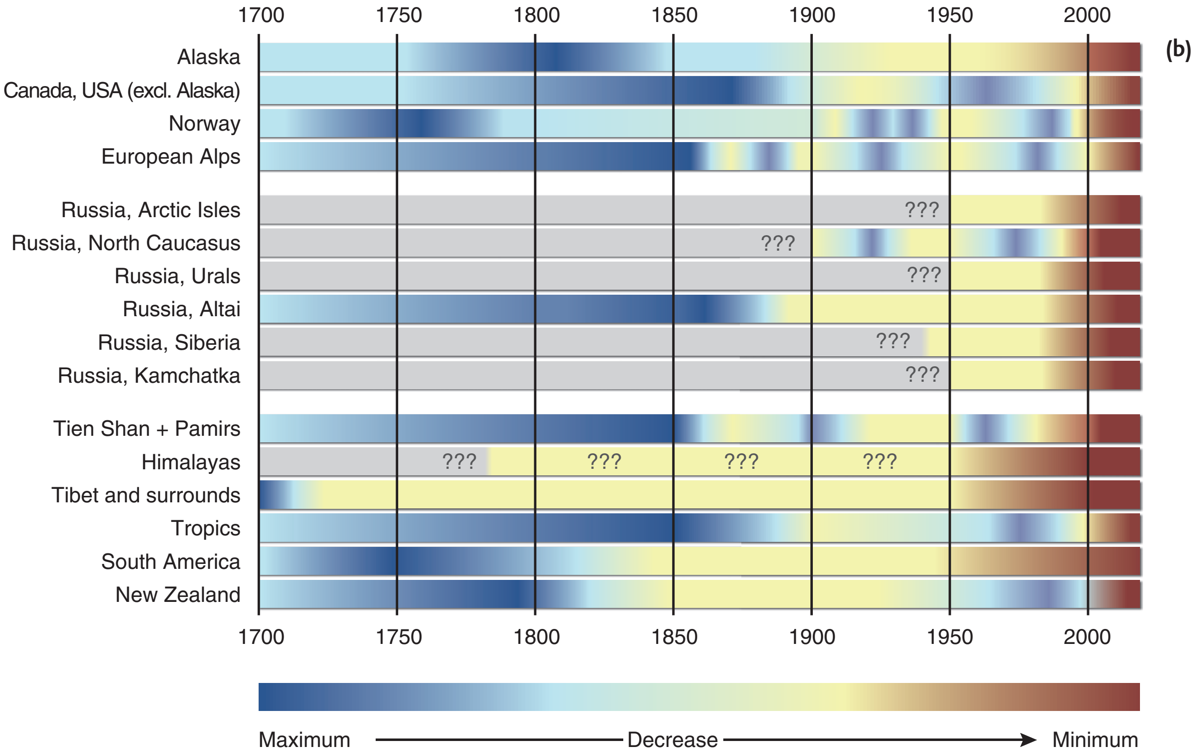
Glaciers form where snow deposited during the cold/humid season does not entirely melt during warm/dry times. These conditions are widespread in the world, so glaciers are found from the poles to the tropics. This section looks at representative mountain ranges, ordered by Northern and Southern Hemisphere from west to east. The ice sheets in Antarctica and Greenland are discussed in the previous chapter (6A). See inside front cover for a map of worldwide glacier distribution.

Figure 6B.11: Overview of world glaciers and ice caps.
(a) Glaciers and ice caps around the world. The total area of glaciers and ice caps, without the ice sheets and surrounding glaciers and ice caps in Greenland and Antarctica, sums up to 540 000 km^2.

Source: Data from Dyurgerov and Meier 2005[122]

(b) Overview on glacier changes since the end of the Little Ice Age, summarizing the regional glacier fluctuations based on the data presented in this section.


(a)
New Guinea, Irian Jaya
Africa
New Zealand
Siberia
Subantarctic Islands
Europe
South America
Svalbard and surrounds
North America (excluding Alaska and Canadian Arctic islands)
Russian Arctic islands
Alaska
Asia
Canadian Arctic islands
0
50 000
100 000
150 000 km²


(b)
1700
1750
1800
1850
1900
1950
2000
Alaska
Canada, USA (excl. Alaska)
Norway
European Alps
Russia, Arctic Isles
Russia, North Caucasus
Russia, Urals
Russia, Altai
Russia, Siberia
Russia, Kamchatka
Tien Shan + Pamirs
Himalayas
Tibet and surrounds
Tropics
South America
New Zealand
???
Maximum
Decrease
Minimum

North America

Arctic islands and mountain ranges

By far the largest area of glaciers and ice fields are found in Canada (about 201 000 km^2)[88], followed by Alaska (about 75 000 km^2)[89] with about 700 km^2 in the rest of the USA[90]. Glaciers and ice fields are concentrated in the High Arctic (Figure 6B.12) and western cordillera.

Glaciers reached their Little Ice Age maximum extent between the early 18th and late 19th century in Alaska[91] and in the mid to late 19th century in Canada and the continental USA[92]. Subsequently, a general retreat of glaciers developed, particularly at lower elevations and southern latitudes[91]. There are exceptions to this trend: southern cordilleran and Alaskan coastal glaciers slowed their retreat or advanced in response to cooler summers and heavier snowfall in the 1950s to 1970s[93,94]. Since that time the glaciers have continued to retreat and the retreat has accelerated since the 1970s. In the western cordillera they have now lost about 25 per cent of their area since the Little Ice Age[90,95]. In the northwest continental USA and southwest Canada, accelerated retreat coincided with a shift in atmospheric circulation patterns that occurred during 1976–1977[96,97].

Airborne laser altimetry studies on 67 glaciers (representing about 20 per cent of the glacierized area in Alaska and neighbouring parts of Canada) show a mean annual thickness change of –0.5 m water equivalent from the mid 1950s to the mid 1990s, and more than three times as much (–1.8 m water equivalent) from the mid 1990s to 2000–2001 based on a sub-sample of 28 glaciers[26].

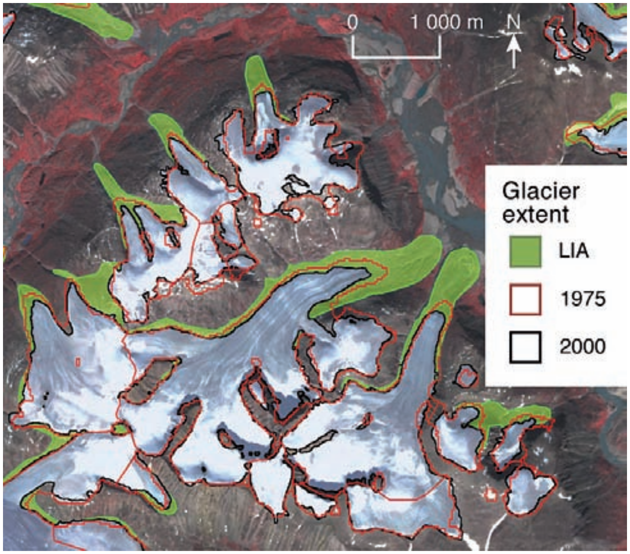


Figure 6B.12: Glacier shrinking on Cumberland Peninsula, Baffin Island, Canadian Arctic. A new glacier inventory based on satellite data shows that the glacier cover reduced by about 22 per cent between the Little Ice Age (LIA) maximum extent and 2000.

Source: Data and figure from F. Svoboda, University of Zurich, Switzerland

Norway

Mainland Norway's glacier cover is about 2600 square km[98,99]. The maximum recent extent culminated around 1750. At that time many farms and much farmland were buried by ice. Since then there has been a general retreat but with large regional variations; some areas kept the maximum extent until the late 19th century. Since 1900 glaciers have retreated but with short advances around 1910, around 1930 and in the 1990s. In contrast to glaciers in most of the world, glaciers along the western coast advanced from the 1970s to the end of the 1990s as a result of high winter snowfall. Since 2000, all glaciers have been retreating considerably[100,101].

The ice masses of the Svalbard archipelago, north of mainland Norway, cover 36 600 square km[102]. Long-term mass balance measurements from Austre Broeggerbreen and Midre Lovénbreen show a strong trend in ice loss over the past 40 years[103].

A glacier on Svalbard.
Photo: Sebastian Gerland, Norwegian Polar Institute

European Alps

Glaciers in the European Alps reached their recent maximum extent around 1850[104–106]. The overall area loss since then is estimated to be about 35 per cent until the 1970s, when the glaciers covered a total area of 2 909 km^2, and almost 50 per cent by 2000[19]. Total ice volumes in 1850, the 1970s and 2000 are estimated to be about 200 km^3, 100 km^3 and 75 km^3, respectively[19]. Observations show intermittent glacier re-advances in the 1890s, 1920s and 1970–1980s[107–109] (Figure 6B.13). After 1985 an acceleration in glacial retreat has been observed, culminating in an annual ice loss of 5–10 per cent of the remaining ice volume in the extraordinarily warm year of 2003[110]. The strong warming has made disintegration and downwasting increasingly predominant processes of glacier decline during the most recent past[111].

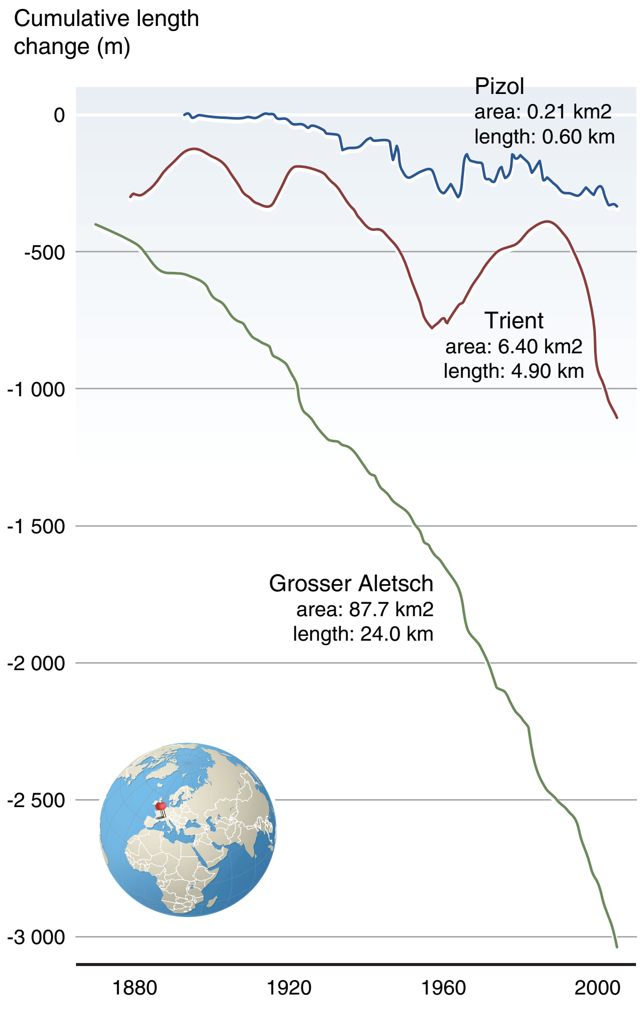


Figure 6B.13: Glacier front variations in the European Alps. Large Alpine glaciers have retreated continuously since the mid-19th century, whereas steep mid-sized glaciers reacted with re-advances in the 1890s, 1920s and between the 1970s and1980s due to the somewhat cooler and wetter periods. Small glaciers feature a high annual variability with a clear shrinking trend.

Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland

Russia

Arctic islands and mountain ranges

The following details on the glacier distribution and changes in Russia are based on a monograph edited by Kotlyakov and others[112].

Russia's glaciers and ice fields are concentrated in its Arctic islands where their extent is about 56 000 km^2. Glaciers are widely dispersed on mountain ranges from the Urals to Kamchatka, with an extent of about 3600 km^2 reported in the period 1950–1970 (USSR Glacier Inventory). There is a pattern of general retreat that is mainly at lower elevations and southern latitudes that in some places is dramatic. For example, in the Arctic islands over the last 50 years there has been a reduction of only 1.3 per cent of glacierized area whereas glaciers in the North Caucasus retreated by about 50 per cent in the last century with extreme melting and abrupt decrease in area occurring in the period 1998–2001.

There has been considerable variability in the retreat of mountain glaciers, as would be expected in so large a geographic area. In the North Caucasus glacier advances were reported in the 20th century and in Kamchatka both advances and retreats have occurred on glaciers of the Avachinskaya and Klyuchevskaya groups of volcanoes, possibly connected with volcanic activity. In other parts of Kamchatka there is a general retreat with glaciers in the coastal Kronotsky peninsula being most sensitive to climate change.

Since the mid-19th century glaciers in the Altay have continuously degraded but the rate has slowed in recent years. Direct mass balance measurements at Maliy Aktru Glacier show a slightly negative mean annual mass balance (about –0.09 m water equivalent) over the period 1962–2005 (Figure 6B.14).

In some mountain ranges topographic changes have been dramatic. In the Urals some glaciers have disappeared completely and in the North Caucasus large glaciers have been reduced to separated remnants.

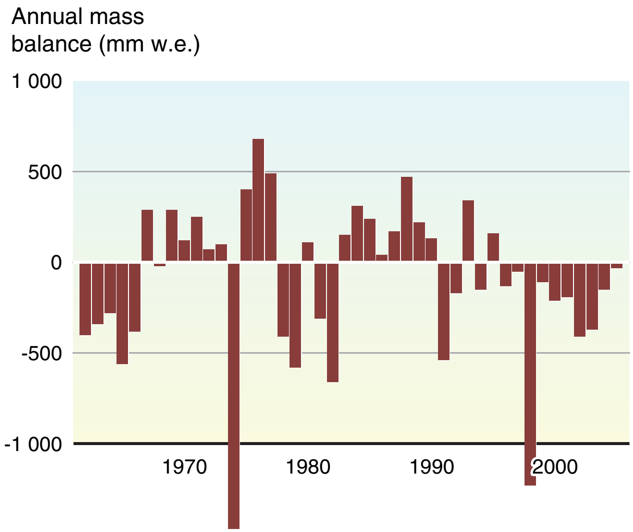


Figure 6B.14: Mass balance of Maliy Aktru Glacier, Russian Altai. Measurements on this valley-type glacier in the North Chuyskiy Range show a slightly negative annual mass balance trend culminating in an ice loss of about 4 m water equivalent over the period 1964–2005.
Photo: Y.K. Narozhniy (taken in July 1992); data from the World Glacier Monitoring Service, Zurich, Switzerland

Central Asian Tien Shan and Pamirs

Overall glacier area of Tien Shan (Central Asian republics and China) and Pamirs was estimated by Dyurgerov and Meier[122] at 15 417 km^2 and 12 260 km^2, respectively, with their maximum recent extent being between the 17th and mid 19th centuries[39,113–115].

Figure 6B.15: Shrinking of Fedchenko Glacier in the Pamirs of Tajikistan. The debris-covered glacier tongue retreated by more than 1 km since 1933 and lowered by about 50 m since 1980.
Photo: V. Novikov (taken in summer 2006); data from the Tajik Agency on Hydrometeorology

Significant loss of glaciers in Central Asia began around the 1930s, and become more dramatic in the second half of the 20th century and continue into the 21st century. Glacier area was reduced by 25–30 per cent in the Tien Shan, by 30–35 per cent in the Pamirs, including its largest Fedchenko Glacier (Figure 6B.15), and by more than 50 per cent in northern Afghanistan[39,113,115–117].

Glaciers in higher altitudes (above 4 000 m above sea level) experienced less pronounced ice losses[39,113,119]. Total retreat has reached several kilometres for many larger glaciers, some hundred metres for smaller ones, and many hundreds of small glaciers have vanished[39,113]. Glacier degradation is accompanied by increasing debris cover on many glacier termini and the formation of glacier lakes[39,113]. See also the box on glaciers and water supply in Central Asia.

Glaciers and water supply in Central Asia

On average, glacier melt contributes 10–20 per cent of the total river runoff in Central Asia[39,120]. During dry and hot years, the input of glacier water into summer river flow could be as high as 70–80 per cent, compared to 20–40 per cent in normal years. This proportion is critical for agriculture – the economic sector that consumes about 90 per cent of water resources and is highly dependent on water availability. During the severe droughts of 2000–2001 in the southern districts of Central Asia, glacier water played a vital role in sustaining agricultural production. Irrigated crops such as cotton have survived, while most rain-fed crops, especially cereals, failed. This has strongly affecting the food security of millions of people in Tajikistan, Afghanistan and Iran. It is expected that glacier recession in the long term could reduce water supply, affecting the agricultural sector and energy security, thereby destabilizing the political situation since many of the rivers are transboundary[121]. In Central Asia, the Amu Darya river basin, where input of glacier water is significant, and the densely populated Ferghana Valley, are among most vulnerable to the impacts of droughts, climate change and glacier degradation.

Himalayas

The ice extent in the Himalayas is estimated to be about 33 050 square km[122]. Observations of individual glaciers indicate annual retreat rates varying from basin to basin – in some instances showing a doubling in recent years compared to the early 1970s. An 8 per cent area loss was observed for glaciers in Bhutan between 1963 and 1993[123]. The Imja Glacier in the Dudh-Koshi basin of the Everest region retreated almost 1600 m between 1962 and 2001 and another 370 m by 2006 (Figure 6B.16). The Gangotri Glacier in Uttaranchal, India, retreated about 2 km between 1780 and 2001[124]. The glacier shrinking is accompanied by the formation of unstable glacial lakes that threaten downstream areas with outburst floods. For a discussion of the impacts of glacier shrinking on water resources, please see the box on the water towers of Asia, at the end of Part 1 of this chapter.

Figure 6B.16: Growth of Imja Tsho Lake, Himalayas. The lake started to form in 1962 at the debris-covered tongue of Imja Glacier and grew to an area of about 1 km^2 by 2006. The growing moraine-dammed lake is potentially hazardous in case of a dam failure.
Photo: Michael Hambrey, SwissEduc (www.swisseduc.ch)/Glaciers online (www.glaciers-online.net); data from the International Centre for Integrated Mountain Development, Nepal

Tibetan Plateau

The Tibetan Plateau and surrounding regions in China have a total glacier area and volume of 59 400 km^2 and 5600 km^3, respectively. Glaciers in China have been retreating with an area loss of about 20 per cent since the Little Ice Age maximum extent in the 17th century[125,126]. Retreat increased during the last century, especially during the past ten years[127,128]. Several monitored glaciers show strong retreat. About 90 per cent of glaciers are retreating, and glacier retreat increases from the continental interior to the coastal margins[127,128]. With the impact of global warming on the region[127,129,130], glacier shrinkage will be faster and pose a serious threat to water resources in this region (see box on the water towers of Asia, at the end of Part 1 of this chapter).

South America

Glaciers in South America cover an area of about 25 700 square km[131], mainly in the Patagonian Icefields, which represent 66 per cent of South America's total ice area[132]. Chile has by far most of the glaciers; Argentina has an important number of ice bodies all along the Andes; Venezuela has less than 2 km^2 of ice at Pico Bolivar[133]. Less than 10 per cent of the glacier area is located in the tropical Andes[134] (see box on tropical glaciers).

In southern Patagonia, the glacial advance appears to have peaked between the late 17th and early 19th centuries[135]. Medium and small glaciers in central Chile and Argentina have shrunk considerably. This will affect the future availability of water resources, as these glaciers can contribute up to 68 per cent of meltwater during dry seasons. (See box on glacier changes and water availability in the tropical Andes). Most of the calving glaciers in Patagonia have also experienced drastic retreat[136], contributing significantly to sea level rise[27,137]. Ice avalanches in the cordillera have resulted in many thousands of deaths (see box on the deadly avalanches of Glaciar 511 in the Cordillera Blanca).

Glacier changes and water availability in the tropical Andes

There is growing evidence that glacier retreat in the tropical Andes has accelerated in recent decades due to atmospheric warming[134]. Ongoing rapid glacier recession was found to have enhanced discharge at the expense of catchments storage[138,139]. The recent increase in runoff is not likely to last very long[140]. In the long run, changes in runoff may occur which could severely affect the availability of water resources for future generations, particularly during dry periods. Short-term increases in stream discharge with critical long-term loss of storage are likely to be widespread over the Cordillera Blanca region. Since glacier melt currently provides a very significant proportion of discharge of the Rio Santa River, the latter is also likely to diminish with continued glacier loss.

The melting of glaciers may lead to water shortages for millions of people. Among the Andean countries at risk are Bolivia, Ecuador and Peru, where glaciers feed rivers all year round. On the Pacific side of Peru, 80 per cent of the water resources originate from snow and ice melt. During the dry seasons, glacier-fed surface waters often constitute the sole water resource for domestic, agricultural (Figure 6B.17) and industrial uses, not only for rural areas but also for major cities. A reduced glacier runoff will aggravate the problems associated with the water availability, especially if a potential warming leads to earlier snow melt, regional reductions in precipitation and an increase in evaporation[1,141].

Figure 6B.17: Glaciers and irrigation. Irrigation ditches on the slopes of Huascarán, Cordillera Blanca, Peru, support extensive agriculture during the dry season. Most water comes from nearby glaciers.
Photo: Michael Hambrey, SwissEduc (www.swisseduc.ch)/Glaciers online (www.glaciers-online.net)

Deadly ice avalanches of Glaciar 511 in the Cordillera Blanca, Peru

Many disasters have been recorded from the glaciers in the Cordillera Blanca. The 1962 and 1970 events originating from Glaciar 511 on the Nevados Huascarán[142] (Figure 6B.18), the highest peak of which is at 6768 m above sea level in the Peruvian Andes, were particularly severe. On 10 January 1962, an ice avalanche took place with an estimated starting volume of 10 million m^3; the avalanche travelled down 16 km and destroyed the city of Ranrahirca, where 4000 people died. On 31 May 1970, the most catastrophic rock-ice avalanche known in history was triggered at 3:23 p.m. by a strong earthquake with a magnitude of 7.7. The avalanche originated from a partially overhanging cliff at 5400 to 6500 m above sea level, where the fractured granite rock of the peak was covered by a 30 metre thick glacier. The avalanche, which had an estimated volume of 50 to 100 million m^3, travelled 16 km to Rio Santa down a vertical drop of 4 km. Along its path, the avalanche overrode a hill in the downstream area and completely destroyed the city of Yungay, claiming about 18 000 lives.

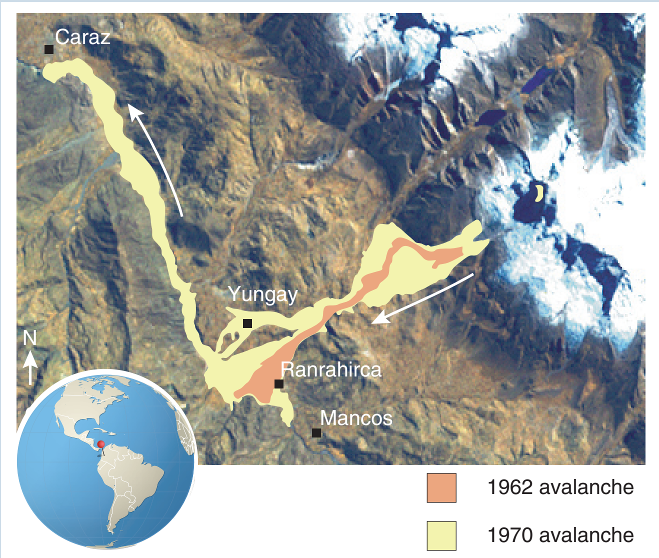


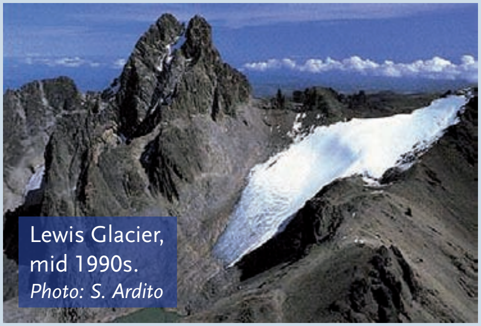
Figure 6B.18: Ice avalanches of the Nevados Huascarán in Peru. The severe events in 1962 and 1970 originated from Glaciar 511 and claimed many thousands of lives.

Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland and figure by UNEP's DEWA/GRID-Europe, Geneva, Switzerland

Tropical glaciers

Tropical glaciers are found in the high mountains of the Andes in Colombia (Figure 6B.19), Venezuela, Equador, Peru and Bolivia, as well as in the high mountains of East Africa (Figure 6B.20) and Irian Jaya, Indonesia. Around the period 1950–1990 they covered about 2760 km^2 with about one quarter in the Peruvian Cordillera Blanca[143]; this area had shrunk to about 2500 km^2 for the period 2000–2005[144]. The maximum extents of tropical glaciers occurred between the second half of the 17th century in Bolivia[145] and the late 19th century in East Africa[146]. From then, glacier shrinkage was more or less synchronous with the global one. Shrinkage rates were strongest in the 1940s, followed by a pause around the 1970s with several front advances. Since then, glaciers have again begun to retreat[134].

Since the publication of IPCC 2001, evidence has increased that changes in the mass balance of tropical glaciers are mainly driven by coupled changes in energy and mass fluxes related to interannual variations of regional-scale wet and dry seasons. Variations in atmospheric moisture content affect incoming solar radiation, precipitation and albedo, atmospheric longwave emission, and sublimation. At a large scale, the mass balance of tropical glaciers strongly correlates with tropical sea surface temperature anomalies and related atmospheric circulation modes[1].



Lewis Glacier, mid 1990s.
Photo: S. Ardito

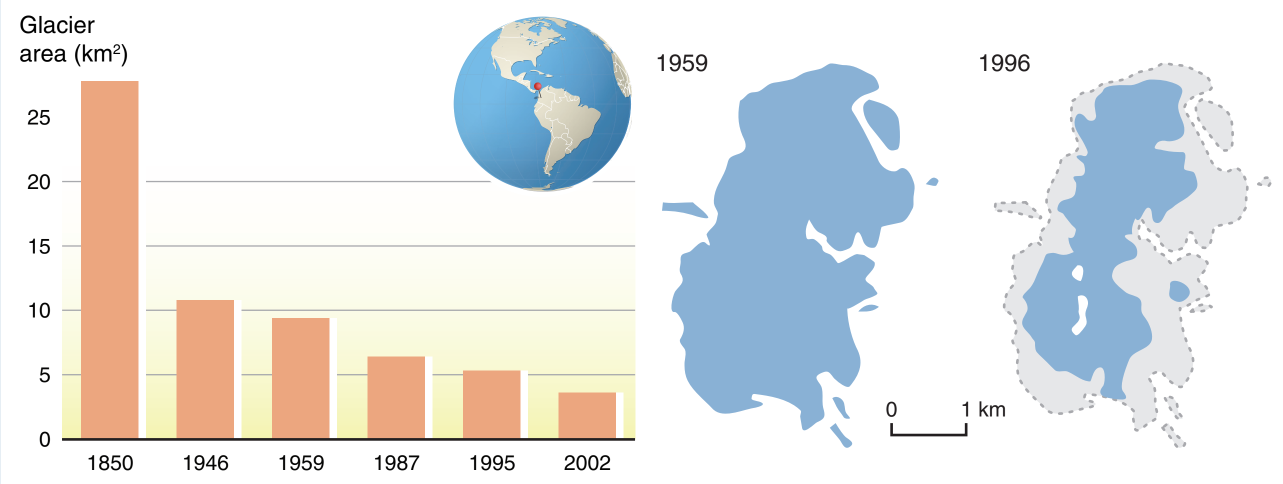


Figure 6B.19: Glacier changes on Nevado de Santa Isabel, Colombia. This inactive volcano lost about 87 per cent of its ice cover between 1850 and 2002.

Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland

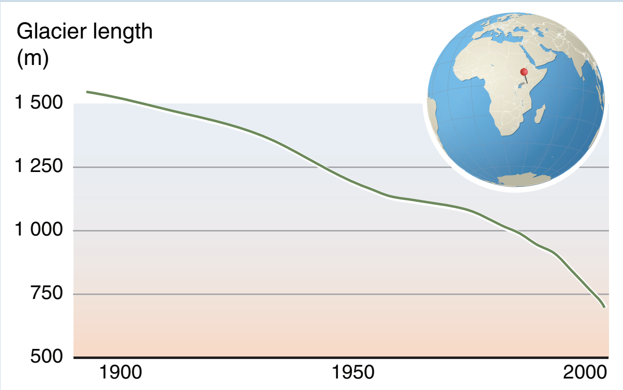


Figure 6B.20: Shrinking Lewis Glacier, Mount Kenya. This tropical glacier retreated by more than 800 m between 1893 and 2004 and lost almost 16 m water equivalent of its thickness between 1979 and 1996.

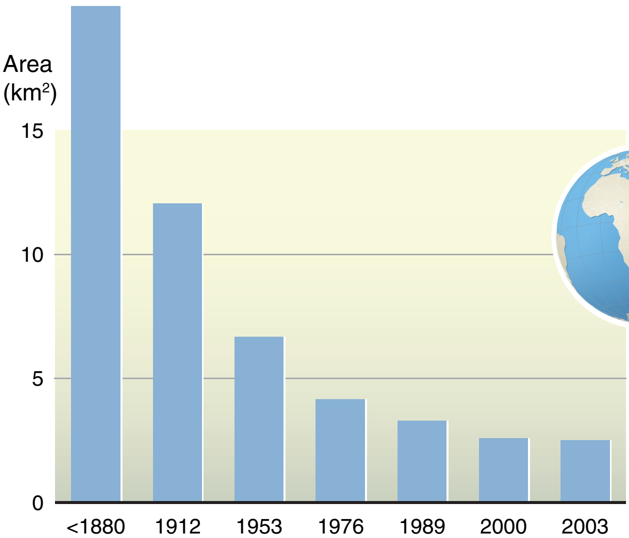
Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland

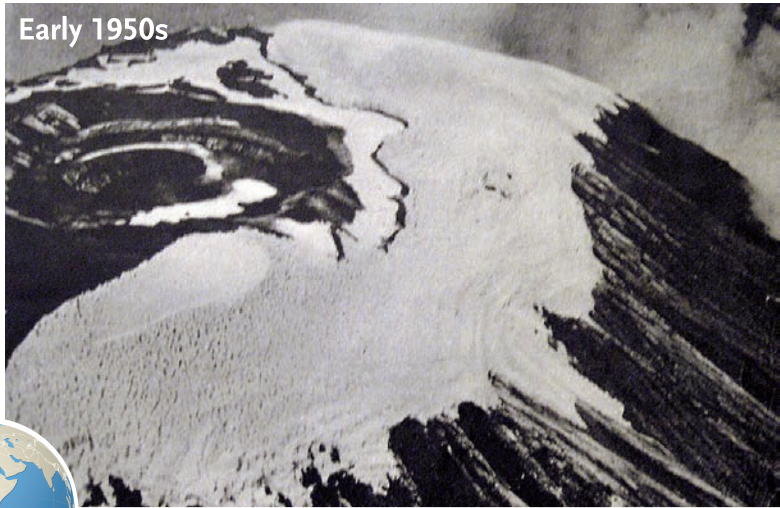
Kersten glacier on Mt. Kilimanjaro.
Photo: Georg Kaser, Tropical Glacier Group, University of Innsbruck

Photo: Georg Kaser, Tropical Glacier Group, University of Innsbruck

African Mountains

Glaciers are found on three mountains in Africa: Rwenzori Mountains (5109 m above sea level), Mount Kenya (5199 m above sea level) and Kilimanjaro (5895 m above sea level) (Figure 6B.21), all located near the equator in East Africa. Recent retreat of these glaciers began around the 1880s as a result of a decrease in precipitation and an increase in solar radiation from reduced cloudiness. Later





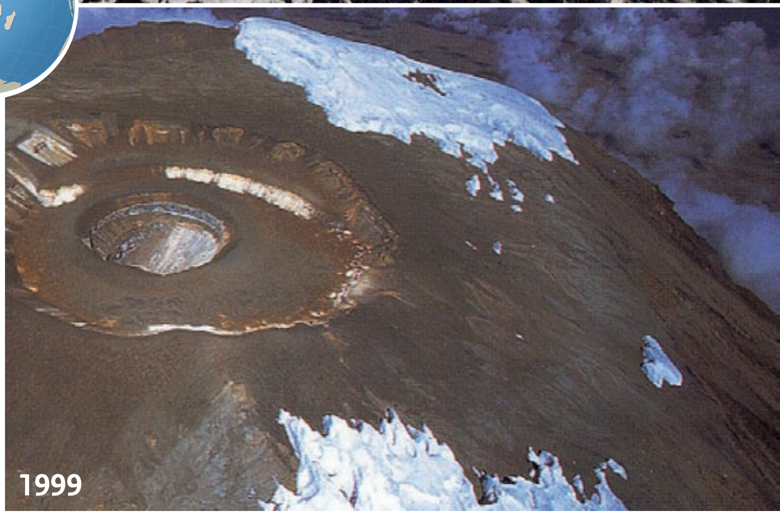


Figure 6B.21: Melting ice on Mount Kilimanjaro, East Africa. The graph shows the drastic reduction of the ice cover since the first observations in 1880, based on historical maps, aerial photographs and satellite images. The oblique photos illustrate the shrinking of the ice cover between the early 1950s and 1999.
Photos: (early 1950s) John West, (1999) Javed Jafferji. Data from Cullen and others 2006[150]

in the 20th century, increased temperature became an additional driver, although its relative importance is still debated[147–149]. Over the last century (1906–2006), these glaciers have lost an estimated 82 per cent of their area – from approximately 21 to 3.8 km^2. Close to 50 per cent of the glaciers on the Rwenzori Mountains, Mount Kenya and Kilimanjaro have disappeared, while larger glaciers – particularly on Kilimanjaro – have been fragmented[148,150,151].

The most pronounced impact of these receding glaciers is on the scenery. Unlike mountain glaciers in higher latitudes, the shrinking of the East African glaciers will have no significant impact on water resources. The hydrology on these mountains is dominated by extensive forest belts (hundreds to thousands times larger than the glaciated area) with a much higher annual rainfall. If all the glaciers on Kilimanjaro – which has the highest glacier to forest area ratio – were to melt in just one year, the resulting loss in water resources would be equivalent to only four per cent of the total annual rainfall over the forest belt[152].

New Zealand

Apart from a few glaciers on Mt. Ruapehu volcano in the North Island, the bulk of New Zealand's glaciers are located in the Southern Alps. They reached their maximum recent extent towards the end of the 18th century, with only minor retreat until the end of the 19th century[153]. Total glacier area was 1158 km^2 in 1978, with an estimated total ice volume of about 53 cubic km[154,155]. The overall estimated area and volume changes since the mid of the 19th century are –49 and –61 per cent, respectively[156]. Since the mid-1970s, the glaciers overall have experienced positive mass balances with those having short response times advancing noticeably from the mid-1980s. This period of advances appeared to be coming to an end at the beginning of the new century[157]. A recent study[85] estimates a net ice volume loss over the period 1977–2005 of 17 per cent, mainly due to calving into lakes and associated wasting at glacier tongues. Mass loss due to changes in glacier thickness, excluding that related to lake growth, has contributed only 7 per cent to the overall ice loss since 1977.

References

[1] IPCC (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M.C. Marquis, K. Averyt, M. Tignor and H.L. Miller). Intergovernmental Panel on Climate Change, Cambridge and New York

[2] Paterson, W.S.B. (1994). *The physics of glaciers. 3rd edition*. Pergamon Press, Oxford

[3] Shumsky, P.A. (1964). *Principles of structural glaciology. Translated from the Russian by D. Kraus*. Dover Publications Inc., New York

[4] Haeberli, W. and Burn, C.R. (2002). Natural hazards in forests: Glacier and permafrost effects as related to climate change. In *Environmental Change and Geomorphic Hazards in Forests. IUFRO Research Series* (ed. R.C. Sidle). CABI Publishing, Wallingford/New York

[5] Meier, M.F. (1984). The contribution of small glaciers to sea level rise. *Science*, 226, 1418– 1421

[6] Nye, J.F. (1960). The response of glaciers and ice-sheets to seasonal and climatic changes. *Proceedings of the Royal Society of London*, A(256), 559–584

[7] Oerlemans, J. (2001). *Glaciers and climate change*. A.A. Balkema Publishers, Lisse

[8] Kuhn, M. (1981). Climate and glaciers. *IAHS*, 131, 3–20

[9] Haeberli, W. (1998). Historical evolution and operational aspects of worldwide glacier monitoring. In *Into the second century of world glacier monitoring: Prospects and strategies* (eds. W. Haeberli, M. Hoelzle, and S. Suter). UNESCO, Paris

[10] Haeberli, W. and 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

[11] Jóhannesson, T., Raymond, C. and Waddington, E. (1989). Timescale for adjustment of glaciers to changes in mass balance. *Journal of Glaciology*, 35(121), 355–369

[12] Kaser, G., Georges, C., Juen, I. and Mölg, T. (2005). Low latitude glaciers: Unique global climate indicators and essential contributors to regional fresh water supply. A conceptual approach. In *Global Change and Montain Regions - A State of Knowledge Overview* (eds. U.M. Huber, H.K.M Burgmann, and M.A. Reasoner). Springer, Dordrecht

[13] Haeberli, W., Huggel, C., Kääb, A., Oswald, S., Polkvoj, A., Zotikov I. and Osokin, N. (2004). The Kolka-Karmadon rock/ice slide of 20 September 2002 - an extraordinary event of historical dimensions in North Ossetia (Russian Caucasus). *Journal of Glaciology*, 50(171), 533–546

[14] Solomina, O., Haeberli, W., Kull, C. and Wiles, G. (2007). Historical and Holocene glacier-climate variations: General concepts and overview. In print

[15] Grove, J.M. (2004). *Little Ice Ages: Ancient and modern*. Routledge, London and New York

[16] Koch, J. and Clague, J.J. (2006). Are insolation and sunspot activity the primary drivers of Holocene glacier fluctuations? *PAGES News*, 14(3), 20–21

[17] Solanki, S.K., Usoskin, I.G., Kromer, B., Schüssler, M. and Beer, J. (2004). Unusual activity of the sun during recent decades compared to the previous 11,000 years. *Nature*, 431, 1084–1087

[18] Abbott, M.B., Wolfe, B.B., Wolfe, A.P., Seltzer, G.O., Aravena, R., Mark, B.G., Polissar, P.J., Rodbell, D.T., Rowe, H.D. and Vuille, M. (2003). Holocene paleohydrology and glacial history of the central Andes using multiproxy lake sediments studies. *Palaeogeography, Palaeoclimatology, Palaeocology*, 194, 123-138

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

[20] Haeberli, W. (2004). Glaciers and ice caps: Historical background and strategies of worldwide monitoring. In *Mass balance of the Cryosphere* (eds. J.L. Bamber and A.J. Payne). Cambridge University Press, Cambridge

[21] Hoelzle, M., Haeberli, W., Dischl, M. and Peschke, W. (2003). Secular glacier mass balances derived from cumulative glacier length changes. *Global and Planetary Change*, 36, 295–306

[22] Kääb, A. and GAPHAZ Working Group (2006). Towards a set of general recommendations for assessing glacier and permafrost hazards in mountains. *EGU Geophysical Research Abstracts*, 8, 04608

[23] Haeberli, W. and Holzhauser, H. (2003). Alpine glacier mass changes during the past two millennia. *Pages News*, 11(1), 13–15

[24] Kaser, G., Cogley, J.G., Dyurgerov, M.B., Meier, M.F. and Ohmura, A. (2006). Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004. *Geophysical Research Letters*, 33(L19501), doi. 10.1029/2006GL027511

[25] Raymond, C., Neumann, T.A., Rignot, E., Echelmeyer, K., Rivera, A. and Casassa, G. (2005). Retreat of Glacier Tyndall, Patagonia, over the last half-century. *Journal of Glaciology*, 51, 239–247

[26] Arendt, A., Echelmeyer, K., Harrison, W.D., Lingle, G. and Valentine, V. (2002). Rapid wastage of Alaska Glaciers and their contribution to rising sea level. *Science*, 297, 382–386

[27] Rignot, E., Rivera, A. and Casassa, G. (2003). Contribution of the Patagonia icefields of South America to sea level rise. *Science*, 302, 434–436

[28] Kääb, A., Reynolds, J.M. and Haeberli, W. (2005a). Glacier and permafrost hazards in high mountains. In *Global Change and Mountain Regions (A state of knowledge overview)* (eds. U.M Huber, H.K.M Bugmann, and M.A. Reasoner). Springer, Dordrecht

[29] Huggel, C., Haeberli, W., Kääb, A., Bieri, D. and Richardson, S. (2004a). Assessment procedures for glacial hazards in the Swiss Alps. *Canadian Geotechnical Journal*, 41(6), 1068–1083

[30] Richardson, S.D. and Reynolds, J.M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International*, 65(66), 31–47

[31] Huggel, C., Kääb, A. and Salzmann, N. (2004b). GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery. *Norwegian Journal of Geography*, 58, 61–73

[32] Carey, M. (2005). Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change*, 47(1–2), 122–134

[33] Haeberli, W., Kääb, A., Vonder Mühll, D. and Teysseire, P. (2001). Prevention of debris flows from outbursts of periglacial lakes at Gruben, Valais, Swiss Alps. *Journal of Glaciology*, 47(156), 111–122

[34] Watanabe, T., Ives, J.D. and Hammond, J.E. (1994). Rapid growth of a glacier lake in Khumbu Himal, Nepal: Prospects for a catastrophic flood. *Mountain Research and Development*, 14(4), 329–340

[35] Stepanov, B. (2006). *Global warming and mudflow activity*. Kazakh Research Institute on Meteorology and Climate, Almaty (in Russian)

[36] Gorbunov, A. and Severski, E. (2001). *Mudflows of Almaty: Historical insight*. Almaty (in Russian)

[37] OCHA (1998). *Emergencies overview in 1998*. United Nations Office for the Coordination of Humanitarian Affairs, New York

[38] Tajik Ministry of Emergencies (2002). *Overview of natural and anthropogenic hazards in Tajikistan in 2002*. Dushanbe (in Tajik and Russian)

[39] Yablokov, A. (2006). Climate change impacts on the glaciation in Tajikistan. In *Assessment report for the Second National Communication of the Republic of Tajikistan on climate change*. Tajik Met. Service, Dushanbe (in Russian)

[40] Novikov, V. (2002). Severe hydro-meteorological events and their fluctuation, report and poster presentation. In: *WMO's Technical Conference on Data Processing and Forecasting Systems, 2–3 December 2002 Cairns, Australia*

[41] Pralong, A. and Funk, M. (2005). On the instability of hanging glaciers. *Journal of Glaciology*, 52(176), 31–48

[42] Salzmann, N., Kääb, A., Huggel, C., Allgöwer, B. and Haeberli, W. (2004). Assessment of the hazard potential of ice avalanches using remote sensing and GIS-modelling. *Norwegian Journal of Geography*, 58, 74–84

[43] Margreth, S. and Funk, M. (1999). Hazard mapping for ice and combined snow/ice avalanches: Two case studies from the Swiss and Italian Alps. *Cold Regions Science and Technology*, 30, 159–173

[44] Huggel, C. (2007). Large mass movements from glacierized and permafrost affected mountain regions: An analysis of potential climate-change related alteration of magnitude-frequency characteristics based on recent events. *EGU Geophysical Research Abstracts*, 9, 04294

[45] Huggel, C., Zgraggen-Oswald, S., Haeberli, W., Kääb, A., Polkvoj, A., Galushkin, I. and Evans, S.G. (2005). The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: Assessment of extraordinary avalanche formation and mobility and application of QuickBird satellite imagery. *Natural Hazards and Earth System Sciences*, 5, 173–187

[46] Kotlyakov, V.M., Rototaeva, O.V. and Nosenko, G.A. (2004). The September 2002 Kolka glacier catastrophe in North Ossetia, Russian Federation: Evidence and analysis. *Mt. Res. and Dev.,* 24(1), 78–83

[47] Kääb, A., Wessels, R., Haeberli, W., Huggel, C., Kargel, J.S. and Khalsa, S.J.S. (2003). Rapid ASTER imaging facilitates timely assessment of glacier hazards and disasters. *EOS Transactions American Geophysical Union*, 84(13), 117–121

[48] Jakob, M. and Hungr, O. (2005). *Debris flow hazards and related phenomena*. Springer, Chichester

[49] Rickenmann, D. and Zimmermann, M. (1993). The 1987 debris flows in Switzerland: Documentation and analysis. *Geomorphology*, 8, 175–189

[50] Zimmermann, M. and Haeberli, W. (1992). Climatic change and debris flow activity in high mountain areas: A case study in the Swiss Alps. *Catena Supplement*, 22, 59–72

[51] Thouret, J.C. (1990). Effects of the November 13, 1985 eruption on the snow pack and ice cap of Nevado del Ruiz volcano, Colombia. *Journal of Volcanology and Geothermal Research*, 41, 177–201

[52] Major, J.J. and Newhall, C.G. (1989). Snow and ice perturbation during historical volcanic eruptions and the formation of lahars and floods. *Bulletin of Volcanology*, 52, 1–27

[53] Huggel, C., Ceballos, J.L., Ramírez, J., Pulgarín, B. and Thouret, J.C. (2007). Review and reassessment of hazards owing to volcano-ice interactions in Colombia. In print

[54] Caplan-Auerbach, J. and Huggel, C. (2007). Precursory seismicity associated with frequent, large avalanches on Iliamna Volcano, Alaska. *Journal of Glaciology*, 53(180), 128–140

[55] Hubbard, B., Heald, H., Reynolds, J., Quincey, D., Richardson, S.D., Zapata Luyo, M., Santillan Portilla, N. and Hambrey, M.J. (2005). Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru. *Earth Surface Processes and Landforms*, 30(10), 1251–1264

[56] Watson, R.T. and Haeberli, W. (2004). Environmental threats, mitigation strategies and high-mountain areas. *Royal Colloquium: Mountain Areas – a Global Resource Ambio Special Report*, 13, 2–10

[57] Evans, D.J.A. (2006). Glacial landsystems. In *Glacier Science and Environmental Change* (ed. P.G. Knight). Blackwell, Oxford

[58] Sugden, D. (2006). Changing glaciers and their role in earth surface evolution. In *Glacier Science and Environmental Change* (ed. P.G. Knight). Blackwell, Oxford

[59] Bolles, E.B. (1999). *The ice finders: How a poet, a professor, and a politician discovered the Ice Age*. Counterpoint, Washington D.C.

[60] Lewis, C.F.M. and Teller, J.T. (2006). Glacial runoff from North America and its possible impact on oceans and climate. In *Glacier Science and Environmental Change* (ed. P.G. Knight). Blackwell, Oxford

[61] Andrews, J.T. (2006). Glaciers, oceans, atmosphere and climate. In *Glacier Science and Environmental Change* (ed. P.G. Knight, P.G.). Blackwell, Oxford

[62] Haeberli, W. (2007). Changing views to changing glaciers. In *The darkening peaks: Glacial retreat in scientific and social context* (eds. B. Orlove, E. Wiegandt, and B. Luckman). In print

[63] Royal Swedish Academy of Sciences (2002). The Abisko Agenda: Research for mountain area development. *Ambio Special Report 11*

[64] Jones, G. A. and Henry, G.H.R. (2003). Primary plant succession on recently deglaciated terrain in the Canadian High Arctic. *Journal of Biogeography*, 30(2), 277–296

[65] Hinderer, M., (2001). Late quaternary denudation of the Alps, valley and lake fillings and modern river loads. *Geodinamica Acta*, 14, 231–263

[66] Jansson, P., Hock, R. and Schneider, T. (2003). The concept of glacier storage: A review. *Journal of Hydrology*, 282(1–4), 116–129

[67] Hock, R., Jansson, P. and Braun, L. (2005). Modelling the response of mountain glacier discharge to climate warming. In *Global Change and Mountain Regions - A State of Knowledge Overview. Advances in Global Change Volume 23* (eds. U.M. Huber, M.A. Reasoner and H.K.M. Bugmann). Springer, Dordrecht

[68] Bond, G. (2006). The interaction of glaciers and oceans in the context of changing climate. In *Glacier Science and Environmental Change* (ed. P.G. Knight). Blackwell, Oxford

[69] Mark, B.G. and Seltzer, G.O. (2005). Glacier recession in the Peruvian Andes: Climatic forcing, hydrological impact and comparative rates over time. In *Global Change and Mountain Regions - A State of Knowledge Overview. Advances in Global Change Volume 23* (eds. U.M. Huber, H.K.M Bugmann, and M.A. Reasoner). Springer, Dordrecht

[70] Barnett, T.P., Adam, J.C. and Lettenmaier, D.P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature,* 438(17), 303–309

[71] OcCC (2007). *Klimaänderung und die Schweiz 2050.* Erwartete Auswirkungen auf Umwelt, Gesellschaft und Wirtschaft. OcCC und ProClim, Bern

[72] Beniston, M. (2005). Climate change and its possible impacts in the Alpine region. In *Global change impacts in mountain biosphere reserves.* UNESCO

[73] Dyurgerov, M.B. and Meier, M.F. (2003). Glaciers and the study of climate and sea level change. In *Mass Balance of the Cryosphere* (eds. J.L. Bamber and A.J. Payne). Cambridge University Press, Cambridge

[74] UNEP (2004). *Fall of the water* (ed. C. Nellemann). United Nations Environment Programme/GRID-Arendal, Arendal

[75] Blyth, S., Groombridge, B., Lysenko, I., Miles, L. and Newton, A. (2002). *Mountain Watch: environmental change and sustainable development in mountains.* UNEP-WCMC, Cambridge

[76] Viviroli, D., Weingartner, R. and Messerli, B. (2003). Assessing the hydrological significance of the world's mountains. *Mountain Research and Development*, 23, 32-40

[77] Merz, J., Nakarmi, G., Shrestha, S.K., Dahal, B.M., Dangol, P.M., Dhakal, M.P., Dongol, B.S., Sharma, S, Shah, P.B. and Weingartner, R. (2003). Water: a scarce resource in rural watersheds of Nepal's Middle mountains. *Mountain Research and Development*, 23, 41

[78] Böhner, J. and Lehmkuhl, F. (2005). Environmental change modelling for Central and High asia: Plestocene, present and future scenarios. *Boreas*, 34, 220-231

[79] Zurick, D., Pacheco, J., Shrestha, B. and Bajracharya, B. (2005). *Atlas of the Himalayas.* ICIMOD, Kathmandu

[80] Ives, J. (1997). Comparative inequalities – mountain communities and mountain families. In *Mountains of the World – A Global Priority. A Contribution to Chapter 13 of Agenda 21* (eds. B. Messerli and J. Ives). Parthenon, New York/London

[81] IUCN/WRI (2003). *Moving water*. The World Conservation Union/World Resources Institute. http://www.iucn.org/bookstore/Bulletin/water-1-2003.htm [Accessed 15 March 2007]

[82] Lu, X.X., Ashmore, P. and Wang, J.F. (2003). Seasonal water discharge and sediment load changes in the upper Yangtze, China. *Mountain Research and Development,* 23, 56-64

[83] Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C.N., Dutton, E.G., Forgan, B., Kallis, A., Russak, V. and Tsvetkov, A. (2005). From dimming to brightening: Decadal changes in solar radiation at earth's surface. *Science*, 203, 847–850

[84] Ohmura, A. (2006). Changes in mountain glaciers and ice caps during the 20th century. *Annals of Glaciology*, 43, 361–368

[85] Chinn, T.J., Salinger, J., Fitzharris, B.B. and Willsman, A. (2007). Annual ice volume changes 1977–2005 for the New Zealand Southern Alps. In print

[86] Jones, P.D. and Mann, M.E. (2004). Climate over past millennia. *Reviews of Geophysics*, 42(RG2002), doi:10.1025/2003RG000143

[87] Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B. and Xoplaki, E. (2001). North Atlantic Oscillation: Concepts and studies. *Surveys in Geophysics*, 22, 321–382

[88] Ommanney, C.S.L. (2002). History of glacier investigations in Canada. In *Satellite image atlas of glaciers of the world. U.S. Geological Survey Professional Paper 1386-J* (eds. R.S.Williams Jr. and J.G. Ferrigno). US Geological Survey, Denver

[89] Post, A.S. and Meier, M.F. (1980). A preliminary inventory of Alaskan glaciers. In: *Proceedings of the Riederalp World Glacier Inventory Workshop, September 1987*. IASH Publication, 126, 45–47

[90] Fountain, A.G., Basagic, H.J., Hoffman, M.J. and Jackson, K. (2006). Glacier response in the American West to climate change during the past century. In *Mountain climate 2006* (ed. C.I. Millar). Government Camp, Oregon

[91] Molnia, B.F. (2007). Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate. *Global and Planetary Change*, 56, 23–56

[92] Kaufman, D.S., Porter, S.C. and Gillespie, A.R. (2004). Quaternary alpine glaciation in Alaska, the Pacific Northwest, Sierra Nevada,

and Hawaii. In *The Quaternary Period in the United States* (eds. A.R. Gillespie, S.C. Porter and B.F. Atwater). Elsevier, Amsterdam

[93] LaChapelle, E.R. (1960). Recent glacier variations in western Washington. *Journal of Geophysical Research*, 65(8), 2505–2509

[94] Hubley, R.S. (1956). Glaciers of the Washington Cascade and Olympic Mountains; their present activity and its relation to local climatic trends. *Journal of Glaciology*, 2(19), 669–674

[95] Luckman, B.H. (2000). The Little Ice Age in the Canadian Rockies, *Geomorphology*, 32(3– 4), 357–384

[96] McCabe, G. J., Fountain, A.G. and Dyurgerov, M. (2000). Variability in winter mass balance of Northern Hemisphere glaciers and relations with atmospheric circulation. *Arctic Antarctic and Alpine Research*, 32(1), 64–72

[97] Bitz, C.M. and Battisti, D.S. (1999). Interannual to decadal variability in climate and the glacier mass balance in Washington, Western Canada, and Alaska. *Journal of Climate*, 12(11), 3181–3196

[98] Østrem, G., Haakensen, N. and Melander, O. (1973). Atlas over breer i Nord-Skandinavia. Oslo and Stockholm, Norges Vassdrags og Energiverk. *Meddelelse fra Hydrologisk avdeling*, 22

[99] Østrem G., Selvig, K.D. and Tandberg, K. (1988). Atlas over breer i Sør-Norge. Oslo, Norges Vassdrags og Energiverk. *Meddelelse fra Hydrologisk avdeling*, 61

[100] Nesje, A., Bakke, J., Dahl, S.O., Lie, O. and Matthews, J.A. (2007). Norwegian mountain glaciers in the past, present and future. In print

[101] Andreassen, L.M., Elvehøy, H., Kjøllmoen, B., Engeset, R.V. and Haakensen, N. (2005). Glacier mass balance and length variations in Norway. *Annals of Glaciology*, 42, 317–325

[102] Haeberli, W., Bösch, H., Scherler, K, Østrem, G. and Wallén, C.C. (1989). *World glacier inventory – status 1988.* IAHS(ICSI)–UNEP–UNESCO, Nairobi

[103] Haeberli, W., Noetzli, J., Zemp, M., Baumann, S., Frauenfelder R. and Hoelzle, M. (2005). *Glacier Mass Balance Bulletin No. 8, 2002–2003.* IUGG(CCS)–UNEP–UNESCO–WMO, Zurich

[104] Maisch, M., Wipf, A., Denneler, B., Battaglia, J. and Benz, C. (2000). *Die Gletscher der Schweizer Alpen. Gletscherhochstand 1850, Aktuelle Vergletscherung, Gletscherschwund Szenarien*. Schlussbericht NFP31. 2. Auflage, VdF Hochschulverlag, Zürich

[105] Gross, G. (1987). Der Flächenverlust der Gletscher in Österreich 1850–1920–1969. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 23(2), 131–141

[106] Holzhauser, H.P. and Zumbühl, H.J. (2003). Nacheiszeitliche Gletscherschwankungen. Sonderdruck zum 54. *Geographentag Bern, Hydrologischer Atlas der Schweiz,* Tafel 3.8

[107] Pelfini, M. and Smiraglia, C. (1988). L'evoluzione recente del glacialismo sulle Alpi Italiani: strumenti e temi di ricerca. *Bollettino della Societa Geografica Italiana*, 1–3, 127– 154

[108] Zemp, M., Paul, F., Hoelzle, M. and Haeberli, W. (2007). Glacier fluctuations in the European Alps 1850–2000: An overview and spatio-temporal analysis of available data. In *The darkening peaks: Glacial retreat in scientific and social context* (eds. B. Orlove, E. Wiegandt and B. Luckman). In print

[109] Patzelt, G. (1985). The period of glacier advances in the Alps, 1965 to 1980. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 21, 403–407

[110] Zemp, M., Frauenfelder, R., Haeberli, W. and Hoelzle, M. (2005). Worldwide glacier mass balance measurements: General trends and first results of the extraordinary year 2003 in Central Europe. *Data of Glaciological Studies*, 99, 3–12

[111] Paul, F., Kääb, A., Maisch, M., Kellenberger, T. and Haeberli, W. (2004). Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Research Letters*, 31(L21402), doi:10.1029/2004GL020816

[112] Kotlyakov, V.M. and others (2006). *Glaciation in North and Central Eurasia at present time*. Nauka, Moscow (in Russian with abstract in English)

[113] Yablokov, A. (2004a). Climate change impacts on the glaciation in Tajikistan. In *Assessment report for the First National Communication of the Republic of Tajikistan on climate change*. Tajik Met. Service, Dushanbe (in Russian)

[114] Solomina, O. (1996). Glaciers recession in the mountains of the former USSR after the maximum of the Little Ice Age: Time and scale. In: *The proceedings of Meeting of the Work Group on Geospatial Analysis of Glaciated Environments*. International Union for Quaternary Research, Dublin

[115] Kutuzov, S. (2005). The retreat of Tien Shan glaciers since the Little Ice Age obtained from the moraine positions, aerial photographs and satellite images. In: *PAGES Second Open Science Meeting 10–12 August 2005, Beijing, China*

[116] Podrezov, O., Dikikh, A. and Bakirov, K. (2002). *Variability in the climatic conditions and glacier of Tien Shan in the past 100 years*. Kyrgyz Russian Slavic University, Bishkek (in Russian)

[117] Chub, V. (2000). *Climate change and its influence on natural resource potential of the Republic of Uzbekistan*. Tashkent SANIGMI Press, Tashkent (in Russian)

[119] Shangguan, D., Liu, S., Ding, Y., Ding, L., Xiong, L., Cai, D., Li, G., Lu, A., Zhang, S. and Zhang, Y. (2006). Monitoring the glacier changes in Mutztag Ata and Konggur mountains, east Pamir, based on Chinese Glacier Inventory and recent satellite imagery. *Annals of Glaciology*, 43, 79–85

[120] Aizen, V., Aizen, E., Melack, J. and Dozier, J. (1997). Climatic and hydrologic changes in the Tien Shan, Central Asia. *Journal of Climate*, 10, 1393–1404

[121] Novikov V. (2004). *The impact of climate change on natural resources and socioeconomic systems in Central Asia and its implications for regional environmental security. A case study of the Pamirs and the Tien-Shan mountain environments*. Central European University, Budapest

[122] Dyurgerov, M.B. and Meier, M.F. (2005). Glaciers and the changing earth system: A 2004 snapshot. *INSTAAR Occasional Paper*, 58

[123] Karma, Ageta, Y., Naito, N., Iwata, S. and Yabuki, H. (2003). Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalayas. *Bulletin of Glaciological Research*, 20, p. 29–40

[124] Kargel, J.S. (2005). *An overview of glaciers, glacier retreat, and subsequent impacts in Nepal, India and China*. WWF Nepal, Kathmandu

[125] Su, Z. and Shi, Y. (2002). Response of monsoonal temperature glaciers to global warming since the Little Ice Age. *Quaternary International*, 97(98), 123–131

[126] Shi, Y. and Liu, S. (1999). Estimation of the response of the glaciers in China to the global warming in the 21st century. *Chinese Science Bulletin*, 45(7), 668–672

[127] Yao, T., Liu, S., Pu, J., Shen, Y. and Lu, A. (2004). Glacial retreat High Asia and its influence on water resource in northwest China. *Science in China (series D)*, 47(12), 970–982

[128] Liu, S., Ding, Y., Li, J., Shangguan, D. and Zhang, Y. (2006). Glaciers in response to recent climate warming in western China. *Quaternary Science*, 26(5), 762–771 (in Chinese with English abstract)

[129] Yao, T., Thompson, L.G., Jiao, K., Mosley-Thompson, E. and Yang, Z. (1995). Recent warming as recorded in the Qinghai-Tibetan Cryosphere. *Annals of Glaciology*, 21, 196–200

[130] Yao, T., Li, Z., Thompson, L.G., Mosley-Thompson, E., Wang, Y., Tian, L., Wang, N. and Duan, K. (2006). $\delta^{18}O$ records from Tibetan ice cores reveal differences in climatic changes. *Annals of Glaciology*, 43, 1–7

[131] Casassa, G., Haeberli, W., Jones, G., Kaser, G., Ribstein, P., Rivera, A. and Schneider, C. (2007). Current status of Andean glaciers. *Global and Planetary Change*, doi:10.1016/j.gloplacha.2006.11.013

[132] Naruse, R. (2006). The response of glaciers in South America to environmental change. In *Glacier Science and Environmental Change* (ed. P.G. Knight). Blackwell, Oxford

[133] USGS (1999). Glaciers of South America. In *Satellite image atlas of glaciers of the world. U.S. Geological Survey Professional Paper 1386-J* (eds. R.S.Williams Jr. and J.G. Ferrigno). US Geological Survey, Denver

[134] Kaser, G. and Osmaston, H. (2002). *Tropical Glaciers. International Hydrological Series.* UNESCO-IHP/Cambridge University Press, Cambridge

[135] Villalba, R. (1994). Tree-ring and glacial evidence for the Medieval Warm Epoch and the Little Ice Age in southern South America. *Climate Change*, 26, 183–197

[136] Rivera, A. and Casassa, G. (2004). Ice elevation, areal, and frontal changes of glaciers from National Park Torres del Paine, Southern Patagonia Icefield. *Arctic, Antarctic and Alpine Research*, 36(4), 379–389

[137] Rivera, A., Acuña, C., Casassa, G. and Bown, F. (2002). Use of remote sensing and field data to estimate the contribution of Chilean glaciers to the sea level rise. *Annals of Glaciology*, 34, 367-372

[138] Mark, B.G., McKenzie, J.M. and Gómez, J. (2005). Hydrochemical evaluation of changing glacier meltwater contribution to stream discharge: Callejon de Huaylas, Peru. *Hydrological Sciences Journal*, 50(6), 975–987

[139] Pouyaud, B., Zapata, M., Yerren, J., Gómez, J., Rosas, G., Suárez, W. and Ribstein, P. (2005). Avenir des ressources en eau glaciaire de la Cordillère Blanche. *Hydrological Sciences Journal*, 50(6), 999–1022

[140] Coudrain, A., Francou, B. and Kundzewicz, Z.W. (2005). Glacier shrinkage in the Andes and consequences for water resources - Editorial. *Hydrological Sciences Journal*, 50(6), 925– 932

[141] IPCC (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmen-*

tal Panel on Climate Change (eds. J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson). Intergovernmental Panel on Climate Change, Cambridge

[142] Lliboutry, L., Arnao, B.M., Pautre, A. and Schneider, B. (1977). Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention. *Journal of Glaciology*, 18(79), 239–254

[143] Kaser, G. (1999). A review of the modern fluctuations of tropical glaciers. *Global and Planetary Change*, 22, 93–103

[144] Kaser, G. (2007). Personal communications

[145] Rabatel, A., Machaca, A., Francou, B. and Jomelli, V. (2006). Glacier recession on Cerro Charquini (16°S), Bolivia since the maximum of the Little Ice Age (17th century). *Journal of Glaciology*, 52(176), 110–118

[146] Hastenrath, S. (1995). Glacier recession on Mount Kenya in the context of the global tropics. *Bull. Inst. Fr. Études Andines*, 24(3), 633–638

[147] Taylor, R.G., Mileham, L., Tindimugaya, C., Majugu, A., Muwanga, A. and Nakileza, B. (2006b). Reply to comment by T. Mölg and others on 'Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature'. *Geophysical Research Letters*, 33(L20405), doi:10.1029/2006gl027606

[148] Taylor, R.G, Mileham, L., Tindimugaya, C., Majugu, A., Muwanga, A. and Nakileza, B. (2006a). Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature. *Geophysical Research Letters*, 33(L10402), doi:10.1029/2006gl025962

[149] Mölg, T., Rott, H., Kaser, G., Fischer, A. and Cullen, N.J. (2006). Comment on 'Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature' by R.G. Taylor, L. Mileham, C. Tindimugaya, A. Majugu, A. Muwanga and B. Nakileza. *Geophysical Research Letters*, 33(L20404), doi:10.1029/2006gl027254

[150] Cullen, N.J., Mölg, T., Kaser, G., Hussein, K., Steffen, K. and Hardy, D.R. (2006). Kilimanjaro glaciers: Recent areal extent from satellite data and new interpretation of observed 20th century retreat rates. *Geophysical Research Letters*, 33(L16502), doi:10.1029/2006gl027084

[151] Hastenrath, S. (2005). *Glaciological studies on Mount Kenya 1971–2005*. University of Wisconsin, Madison

[152] Hemp, A. (2005). Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro. *Global Change Biology*, 11, 1013–1023

[153] Winkler, S. (2004). Lichenometric dating of the Little Ice Age maximum in Mt. Cook National Park, Southern Alps, New Zealand. *Holocene*, 14(6), 911–920

[154] Chinn, T.J. (1991). Glacier inventory of New Zealand. Unpublished report of the Institute of Geological and Nuclear Sciences, New Zealand

[155] Chinn, T.J. (2001). Distribution of the glacial water resources of New Zealand. *Journal of Hydrology New Zealand*, 40(2), 139–187

[156] Hoelzle, M., Chinn, T., Stumm, D., Paul, F., Zemp, M. and Haeberli, W. (2007). The application of glacier inventory data for estimating past climate change effects on mountain glaciers: A comparison between the European Alps and the Southern Alps of New Zealand. *Global and Planetary Change*, 56, 69–82

[157] Chinn, T.J., Winkler, S., Salinger, M.J. and Haakensen, N. (2005). Recent glacier advances in Norway and New Zealand; a comparison of their glaciological and meteorological causes. *Geografiska Annaler*, 87A(1), 141–157