Global Glacier Changes: facts and figures

UNEP

wgms
World Glacier Monitoring Service

Contents

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

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

Foreword by UNEP Executive Director

Climate change is now clearly at the top of the world's agenda. This momentum was generated in large part by the *Intergovernmental Panel on Climate Change* (IPCC), which made clear that climate change is already happening and accelerating. As a result of the remarkable efforts of last year, the international community is armed with a powerful combination of authoritative and compelling science, a far-reaching and rising tide of public concern, and powerful declarations of political will voiced at the Bali *Climate Change Conference* held in December 2007.

The *United Nations Development Programme* (UNDP) *2007/2008 Human Development Report* highlighted the devastating effects climate change is already having on the poorest and most vulnerable, making the achievement of the *Millennium Development Goals* more challenging. UNEP's flagship *Global Environment Outlook* report (GEO-4), published in October 2007, concludes that: "Tackling climate change globally will demand political will and leadership, and strong stakeholder engagement. Adaptation to the changes expected is now a global priority. Improved monitoring is needed, and it is urgent to enhance our scientific understanding of the potential tipping points beyond which reversibility is not assured."

Glaciers are a critical component of the earth' system and the current accelerated melting and retreat of glaciers have severe impacts on the environment and human well-being, including vegetation patterns, economic livelihoods, natural disasters, and the water and energy supply. Monitoring glacier changes and providing scientifically-sound, consistent and illustrative facts and figures on glaciers are therefore critical functions in today's world. Glaciers and ice caps are now also one of the *Essential Climate Variables*, a set of core variables in support of the work of organizations such as the *United Nations Framework Convention on Climate Change* (UNFCCC) and the IPCC.

Under the auspices of the *International Council for Science* (FAGS/ICSU), the *International Union of Geodesy and Geophysics* (IACS/IUGG), the *United Nations Educational, Scientific and Cultural Organisation* (UNESCO), the *World Meteorological Organisation* (WMO), and the UNEP, the *World Glacier Monitoring Service* (WGMS) collects and compiles the basic glacier data from all parts of the world and provides information on the state and trends of glaciers in almost all mountain regions. The current publication follows the *Global Outlook for Ice and Snow* that was published by UNEP at the occasion of *World Environment Day* 2007 and complements regular reports by WGMS on *Fluctuations of Glaciers* and *Glacier Mass Balances*. It presents basic information on a range of glaciers and ice caps throughout the world in a concise and illustrative format, serving as a miniature atlas on global glacier changes for a wide range of audiences.

UNEP commends the work of WGMS and partners on this very important global issue and is grateful to all those who contributed to this current comprehensive and illustrative publication on the dramatic changes affecting so many glaciers in so many parts of the world.

Achim Steiner
United Nations Under-Secretary-General and
Executive Director, United Nations Environment Programme

Foreword by WGMS Director

In 2006, a new record annual mass loss was measured on the reference glaciers under observation, whose mass balance has been recorded since the late 1940s as part of internationally coordinated glacier observation programmes. The average annual melting rate of mountain glaciers appears to have doubled after the turn of the millennium in comparison with the already accelerated melting rates observed in the two decades before. The previous record loss in the year 1998 has already been exceeded three times, i.e., in the years 2003, 2004 and 2006, with the losses in 2004 and 2006 being almost twice as high as the previous 1998 record loss. Glaciers and ice caps are indeed key indicators and unique demonstration objects of ongoing climate change. Their shrinkage and, in many cases, even complete disappearance leaves no doubt about the fact that the climate is changing at a global scale and at a fast if not accelerating rate. Anyone can see the changes in glacier extent and understand the basic physical principle of snow and ice melting as temperatures continue to rise: as the glaciers and ice caps on earth grow smaller, the energy content in the climate system and in the environment on which we depend becomes greater.

The task of scientific glacier monitoring networks is to coordinate the worldwide collection of standardised data in order to quantify the rate of change, to compare its magnitude with the range of variability during the pre-industrial times of the Holocene period, to validate projections of possible future climate change based on general circulation and regional climate models, and to anticipate and assess impacts on the environment, the economy and on society. By looking at glaciers or what is left of them, future generations will be able to discern clearly which climate scenario is being played out at the present time. The consequences of snow and ice disappearance for landscape characteristics and natural hazards in high mountain areas will be felt at local to regional scales, while the changes in the water cycle will also affect continental-scale water supply and global-scale sea levels. The degree of glacier vanishing indeed reflects the increasing distance from dynamic equilibrium conditions of the climate system.

Glaciers and ice caps constitute *Essential Climate Variables* (ECV) within the *Global Climate Observing System* (GCOS) and its terrestrial component, the *Global Terrestrial Observing System* (GTOS), as related to the *United Nations Framework Convention on Climate Change* (UNFCCC). The corresponding *Global Terrestrial Network for Glaciers* (GTN-G) is run by the *World Glacier Monitoring Service* (WGMS) at the *University of Zurich*, Switzerland, in cooperation with the *National Snow and Ice Data Center* (NSIDC) at Boulder, Colorado, and the *Global Land Ice Measurement from Space* (GLIMS) initiative. The collected data form the basis for international assessments such as IPCC, or UNEP's recent *Global Outlook for Ice and Snow*. They are frequently analysed and discussed at scientific conferences and in related publications.

It is the task and responsibility of the WGMS to collect and disseminate standardised data on glacier changes worldwide. The standards are documented in the periodical WGMS publications (*Fluctuations of Glaciers* at 5-yearly intervals and the biennial *Glacier Mass Balance Bulletin*) as well as by the corresponding forms and requests for data submission through the national correspondents and principal investigators. The present publication aims at providing a commented and illustrated overview of the distribution and development of glaciers and ice caps based on the currently available database and selected satellite imagery. It was compiled in collaboration with the WGMS network of national correspondents and principal investigators and reviewed by regional glacier experts.

Our sincere thanks go to all the colleagues and friends who generously provided materials, ideas and expertise. It is with their help and with the support of the sponsoring agencies at national and international levels that the glacier community has been able to build up, for more than a century now, a unique treasury of information on the fluctuations in space and time of glaciers and ice caps on earth.

Wilfried Haeberli
Director, World Glacier Monitoring Service

Summary

Changes in glaciers and ice caps provide some of the clearest evidence of climate change, and as such they constitute key variables for early detection strategies in global climate-related observations. These changes have impacts on global sea level fluctuations, the regional to local natural hazard situation, as well as on societies dependent on glacier meltwater. Internationally coordinated collection and publication of standardised information about ongoing glacier changes was initiated back in 1894. The compiled data sets on the global distribution and changes in glaciers and ice caps provide the backbone of the numerous scientific publications on the latest findings about surface ice on land. Since the very beginning, the compiled data has been published by the *World Glacier Monitoring Service* and its predecessor organisations. However, the corresponding data tables, formats and meta-data are mainly of use to specialists.

It is in order to fill the gaps in access to glacier data and related background information that this publication aims to provide an illustrated global view of the available data sets related to glaciers and ice caps, their distribution around the globe, and the changes that have occurred since the maximum extents of the so-called Little Ice Age (LIA).

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

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

In the current scenarios of climate change, the ongoing trend of worldwide and rapid, if not accelerating, glacier shrinkage on the century time scale is most likely of a non-periodic nature, and may lead to the deglaciation of large parts of many mountain ranges in the coming decades. Such rapid environmental changes require that the international glacier monitoring efforts make use of the swiftly developing new technologies, such as remote sensing and geo-informatics, and relate them to the more traditional field observations, in order to better face the challenges of the 21st century.

Fig. 0.1a—b Recession of Morteratsch Glacier, Switzerland, between 1985 and 2007. Source: J. Alean, *SwissEduc* (www.swisseduc.ch) / *Glaciers online* (www.glaciers-online.net).

1 Introduction

Glaciers, ice caps and continental ice sheets cover some ten per cent of the earth's land surface at the present time, whereas during the ice ages, they covered about three times this amount (Paterson 1994, Benn and Evans 1998). The present ice cover corresponds to about three-quarter of the world's total freshwater resources (Reinwarth and Stäblein 1972). If all land ice melted away, the sea level would rise by almost 65 m, with the ice sheets of Antarctica and Greenland contributing about 57 and 7 metres, respectively, and all other glaciers and ice caps roughly half a metre to this rise (IPCC 2007). Glaciers are an inherent component of the culture, landscape, and environment in high mountain and polar regions. They represent a unique source of freshwater for agricultural, industrial and domestic use, an important economic component of tourism and hydro-electric power production, yet they can also constitute a serious natural hazard. Because they are close to the melting point they react strongly to climate change, and thereby provide some of the clearest evidence of climate change and are essential variables within global climate-related monitoring programmes (GCOS 2004).

The cryosphere, derived from the Greek word *kryo* for cold, consists of snow, river and lake ice, sea ice, glaciers and ice caps, ice shelves and ice sheets, and frozen ground (Fig. 1.1). The different cryospheric components can be categorised in a) seasonal and perennial ice, b) surface and subsurface ice c) ice in the sea, in rivers, in lakes and on land. When referring to perennial surface ice on land, one usually differentiates between ice sheets, ice shelves, glaciers and ice caps (Box 1.1). There are fundamental differences in time-scales and processes involved between the different components of the perennial surface-ice on land. Due to the large volumes and areas, the two continental ice sheets actively influence the global climate over time scales of months to millennia. Glaciers and ice caps, with their smaller volumes and areas, react to climatic forcing at typical time scales from years to centuries. The focus of the present publication is on glaciers and ice caps. Good overviews on the state of knowledge concerning all cryospheric components can be found in IGOS (2007), IPCC (2007) and UNEP (2007).

Internationally coordinated glacier monitoring was initiated already as early as 1894 (Box 1.2). To the present day, the active international compilation and publication of standardised glacier data has resulted in unprecedented data sets on the distribution and changes of glaciers and ice caps. These data derived from field measurements and remote sensing provide a fundamental basis for the scientific studies which constitute the present state of knowledge on glacier changes in time and space. Usually, scientific articles report on the methods and main results of glacier investigations. The raw data and meta-data are compiled, published in standardised formats and made readily available in printed and digital form by the World Glacier Monitoring Service (WGMS) and its cooperation partners. These are the US National Snow and Ice Data Center (NSIDC), which is one of the World Data Centers for Glaciology, and the Global Land Ice Measurements from Space (GLIMS) initiative. So far, a status report on the World Glacier Inventory (WGI) was published in 1989 (WGMS 1989) whereas detailed information on glacier fluctuations has been compiled every five years (WGMS 2008, and earlier volumes) and on glacier mass balance every other year (WGMS 2007, and earlier volumes). With the exception of the latter, these products present the data in tabular form with related meta-data, usually comprehensible to specialists.

The aim of this publication is to provide an illustrated global view of (a) the available data basis related to the monitoring of glaciers and ice caps, (b) their worldwide distribution, and (c) their changes since the maximum extents of the Little Ice Age (LIA).

Box 1.1 Perennial surface ice on land

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

Ice shelf: a thick, floating slab of freshwater ice extending from the coast, nourished by land ice. Nearly all ice shelves are located in Antarctica.

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 lakes or the sea.

Ice cap: dome-shaped ice mass with radial flow, usually covering the underlying topography.

Note that drawing a distinction between ice sheets on one hand, and glaciers and ice caps on the other, is in accordance with the definition of the *Essential Climate Variables* as put forth by GCOS (2004). The term 'glacier' is used in this context as a synonym for different types of surface land ice masses including outlet glaciers, valley glaciers, mountain glaciers and glacierets.

Sources: WGMS 1989, WGMS 2005a,b, IPCC 2007, UNEP 2007.

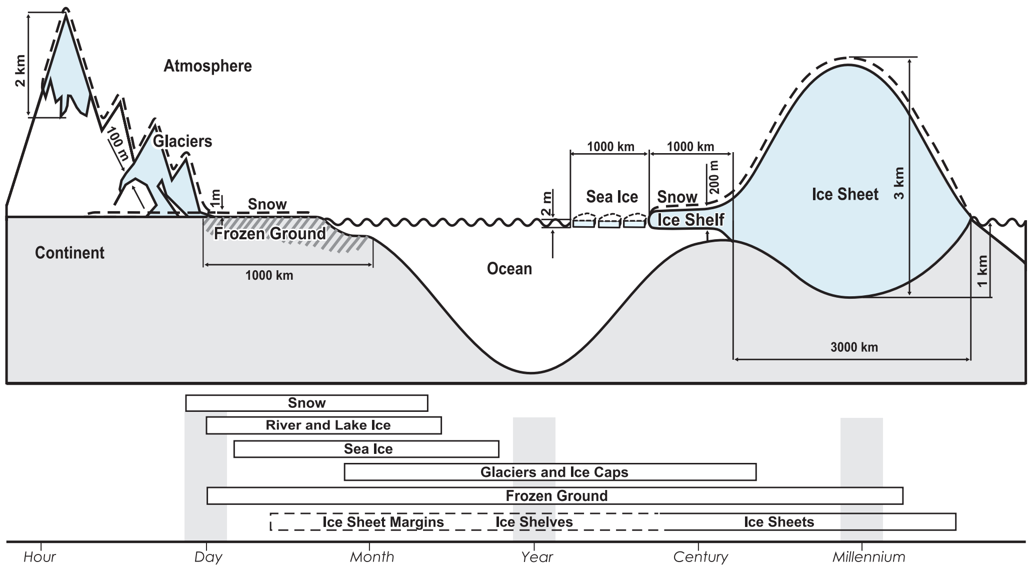

Fig. 1.1 Components of the cryosphere and their typical time scales. Source: Fig. 4.1 of IPCC (2007).

Box 1.2 International glacier monitoring

Worldwide collection of information about ongoing glacier changes was initiated in 1894 with the foundation of the *Commission Internationale des Glaciers* at the *6th International Geological Congress* in Zurich, Switzerland. Today, the *World Glacier Monitoring Service* (WGMS) continues the collection and publication of standardised information on distribution and ongoing changes in glaciers and ice caps. The WGMS is a service of the *International Association of the Cryospheric Sciences* of the *International Union of Geodesy and Geophysics* (IACS, IUGG) and the *Federation of Astronomical and Geophysical Data Analysis Services* of the *International Council for Science* (FAGS, ICSU) and maintains a network of local investigators and national correspondents in all the countries involved in glacier monitoring. In cooperation with the *US National Snow and Ice Data Center* (NSIDC) in Boulder and the *Global Land Ice Measurements from Space* (GLIMS) initiative, the WGMS is in charge of the *Global Terrestrial Network for Glaciers* (GTN-G) within the *Global Climate/Terrestrial Observing System* (GCOS/GTOS). GTN-G aims to combine (a) field 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 monitoring strategy.

More information on the history of international glacier monitoring is found in Haeberli (2007). The GTN-G monitoring strategy is discussed in detail in Haeberli et al. (2000) and Haeberli (2004), with updates on the present state in the biennial GTOS reports (GTOS 2006, GTOS 2008), and illustrated using the example of the European Alps in Haeberli et al. (2007).

Federation of Astronomical and Geophysical Data Analysis Services: www.icsu-fags.org

Global Land Ice Measurements from Space: www.glims.org

Global Terrestrial Network for Glaciers: www.fao.org/gtos/gt-netGLA.html

Global Climate Observing System: www.wmo.ch/pages/prog/gcos/

Global Terrestrial Observing System: www.fao.org/gtos/

International Association of Cryospheric Sciences: www.cryosphericsciences.org

United Nations Environment Programme: www.unep.org

United Nations Educational, Scientific and Cultural Organization: www.unesco.org

US National Snow and Ice Data Center: www.nsidc.org

World Glacier Monitoring Service: www.wgms.ch

World Meteorological Organization: www.wmo.ch

2 Glaciers and climate

Glaciers generally form where snow deposited during the cold/humid season does not entirely melt during warm/dry times. Temperate glaciers not influenced by thick debris cover, calving or surge instabilities are recognised as being among the best climate indicators as their reaction or change provide a signal that is easily understandable to a wider public.

Glaciers form where snow is deposited during the cold/humid season and does not entirely melt during warm/dry periods. This seasonal snow gradually densifies and transforms into perennial firn and finally, after the interconnecting air passages between the grains are closed off, into ice (Paterson 1994). The ice from such accumulation areas then flows under the influence of its own weight and the local slopes down to lower altitudes, where it melts again (ablation areas). Accumulation and ablation areas are separated by the equilibrium line, where the balance between gain and loss of mass is exactly zero. Glacier distribution is thus primarily a function of mean annual air temperature and annual precipitation sums modified by the terrain which influences, for example, the amount of incoming net radiation or the accumulation pattern.

In humid-maritime regions, the equilibrium line is at (relatively) low altitude with warm temperatures and long melting seasons, because of the large amount of ablation required to eliminate thick snow layers (Shumskii 1964, Haeberli and Burn 2002). 'Temperate' glaciers with firn and ice at melting temperature dominate these landscapes. Such ice bodies, with relatively rapid flow, exhibit a high mass turnover and react strongly to atmospheric warming by enhanced melt and runoff. Features of this type are the Patagonian Icefields and the ice caps of Iceland, as well as the glaciers of the western Cordillera of North America, the western mountains of New Zealand (Fig. 2.1) and Norway. The lower parts of such maritime-temperate glaciers may extend into forested valleys, where summer warmth and winter snow accumulation prevent development of permafrost. In contrast, under dry-continental conditions, such as in parts of Antarctica (Fig. 2.2), northern Alaska, Arctic Canada, subarctic Russia, parts of the Andes near the Atacama desert, and in many Central Asian mountain chains, the equilibrium line may be at (relatively) high elevation with cold temperatures and short melting seasons. In such regions, glaciers lying far above the tree line can have polythermal as well as cold firn/ice well below melting temperature, also a low mass turnover, and are often surrounded by permafrost (Shumskii 1964).


Fig. 2.1 Franz-Josef Glacier, 2007

The reaction of a glacier to a climatic change involves a complex chain of processes (Nye 1960, Meier 1984). Changes in atmospheric conditions (solar radiation, air temperature, precipitation, wind, cloudiness, etc.) influence the mass and energy balance at the glacier surface (see Kuhn 1981, Oerlemans 2001). Air temperature thereby plays a predominant role as it is related to the long-wave radiation balance, turbulent heat exchange and solid/liquid precipitation. Over time periods of years to several decades, cumulative changes in mass balance cause volume and thickness changes, which in turn affect the flow of ice via altered internal deformation and basal sliding. This dynamic reaction finally leads to glacier length changes, the advance or retreat of glacier tongues. In short, the advance or retreat of glacier tongues (i.e., the 'horizontal' length change) constitutes an indirect, delayed and filtered but also enhanced and easily observed signal of climatic change, whereas the glacier mass balance (i.e., the 'vertical' thickness change) is a more direct and undelayed signal of annual atmospheric conditions (Haeberli 1998).

Fig. 2.1 Franz-Josef Glacier, New Zealand, is a temperate valley glacier in a maritime climate descending into rain forest. Source: M. Hambrey, *SwissEduc* (www.swisseduc.ch).

Fig. 2.2 Commonwealth Glacier, Taylor Valley, Antarctica, is a cold glacier in a continental climate (10 January 2007). In the background Canada Glacier and frozen Lake Fryxell are shown. Source: D. Stumm, *University of Otago*, New Zealand.

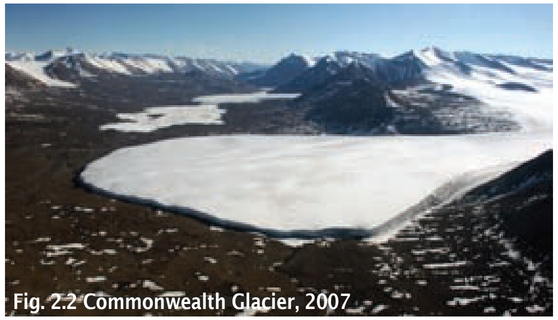
Fig. 2.2 Commonwealth Glacier, 2007

The described complication involved with the dynamic response disappears if the time interval analysed is sufficiently long, i.e., longer than it takes a glacier to complete its adjustment to a climatic change (Jóhannesson et al. 1989, Haeberli and Hoelzle 1995). Cumulative length and mass change can be directly compared over such extended time periods of decades (Hoelzle et al. 2003). Different behaviours are encountered at heavily debris-covered glaciers with reduced melting and strongly limited 'retreat', glaciers ending in deep water bodies causing enhanced melting and calving, and glaciers periodically undergoing mechanical instability and rapid advance ('surge') after extended periods of stagnation and recovery. Glaciers (those not affected by these special conditions) are recognised to be among the best indicators within global climate related monitoring (Box 2.1). They gradually 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.

Box 2.1 Glaciers as climate indicator

Glacier changes are recognised as high-confident climate indicator and as a valuable element in early detection strategies within the international climate monitoring programmes (GCOS 2004, GTOS 2008). Fluctuations of a glacier, which are not influenced by thick debris covers, calving or surge instabilities, are a reaction to climatic forcing. Thereby, the glacier length change (i.e., the advance or retreat) is the indirect, delayed, filtered but also enhanced signal to a change in climate, whereas the glacier mass balance (i.e., the change in thickness/volume) is the direct and un-delayed response to the annual atmospheric conditions (Haeberli and Hoelzle 1995). The mass balance variability of glaciers is well correlated over distances of several hundred kilometres and with air temperature (Lliboutry 1974, Schöner et al. 2000, Greene 2005). However, the glacier mass balance change provides an integrative climatic signal and the quantitative attribution of the forcing to individual meteorological parameters is not straight forward. The energy and mass balance at the glacier surface is influenced by changes in atmospheric conditions (e.g., solar radiation, air temperature, precipitation, wind, cloudiness). Air temperature thereby plays a predominant role as it is related to the radiation balance, turbulent heat exchange and solid/liquid precipitation ratio (Kuhn 1981, Ohmura 2001). The climatic sensitivity of a glacier not only depends on regional climate variability but also on local topographic effects and the distribution of the glacier area with elevation, which can result in two adjacent glaciers featuring different specific mass balance responses (Kuhn et al., 1985). As a consequence, the glacier sensitivity to a climatic change is much related to the climate regime in which the ice is located. The mass balance of temperate glaciers in the mid-latitudes is mainly dependent on winter precipitation, summer temperature and summer snow falls (temporally reducing the melt due to the increased albedo; Kuhn et al. 1999). In contrast, the glaciers in the low-latitudes, where ablation occurs throughout the year and multiple accumulation seasons exist, are strongly influenced by variations in atmospheric moisture content which affects incoming solar radiation, precipitation and albedo, atmospheric longwave emission, and sublimation (Wagnon et al. 2001, Kaser and Osmaston 2002). In the Himalaya, influenced by the monsoon, most of the accumulation and ablation occurs during the summer (Ageta and Fujita 1996, Fujita and Ageta 2000). Cold glaciers in high altitude and the polar regions can receive accumulation in any season (Chinn 1985). As described in the text, strongly diverse mass balance characteristics also exist between glaciers under dry-continental conditions and in maritime regions. As a consequence, analytical or numerical modelling is needed to quantify the above mentioned topographic effects as well as to attribute the glacier mass changes to individual meteorological or climate parameters (e.g., Kuhn 1981, Oerlemans 2001). Modelling is further needed in combination with measured and reconstructed glacier front variations, to compare the present mass changes with the (pre-) industrial variability (e.g. Haeberli and Holzhauser 2003).

3 Global distribution of glaciers and ice caps

A first attempt to compile a world glacier inventory started in the 1970s based mainly on aerial photographs and maps. Up to now, it resulted in a detailed inventory of more than 100 000 glaciers covering an area of about 240 000 km^2, and in preliminary estimates for the remaining ice cover of some 445 000 km^2. Today the task of inventorying glaciers worldwide is continued for the most part based on satellite images.

The need for a worldwide inventory of existing perennial ice and snow masses was first considered during the *International Hydrological Decade* declared by UNESCO for the period of 1965–1974 (Hoelzle and Trindler 1998, UNESCO 1970). The *Temporal Technical Secretariat for the World Glacier Inventory* (TTS/WGI) was established in 1975 to prepare guidelines for the compilation of such an inventory and to collect available data sets from different countries (WGMS 1989). These tasks were continued by its successor organisation, the WGMS, after 1986. In 1989, a status report on the WGI was published including detailed information on about 67 000 glaciers covering some 180 000 km^2 and preliminary estimates for the other glacierised regions, both based on aerial photographs, maps, and satellite images (WGMS 1989). The detailed inventory includes tabular information about geographic location, area, length, orientation, elevation and classification of morphological type (a selection of different types is shown in Figures 3.2–3.5, and more in the other chapters) and moraines, which are related to the geographical coordinates of glacier label points. Due to the different data sources, the entries of the WGI do not refer to one specific year but can be viewed as a snapshot of the glacier distribution around the 1960s. The average map year is 1964 with a standard deviation of eleven years, and a time range from 1901 to 1993. In 1998, the WGMS and the NSIDC agreed to work together, pooled their data sources and made the inventory available online in 1999 via the NSIDC website (Box 3.1). Since then, several plausibility checks, subsequent data corrections and updates of the inventory have been carried out, including updates and new data sets from the former Soviet Union and China. At present the database contains information for over 100 000 glaciers throughout the world with an overall area of about 240 000 km^2 (NSIDC 2008). This corresponds to about half of the total number and roughly one-third of the global ice cover of glaciers and ice caps, which are estimated at 160 000 and 685 000 km^2, respectively, by Dyurgerov and Meier (2005) based mainly on the WGI (WGMS 1989) and additional estimates from the literature.

In 1995, the GLIMS initiative was launched, in close collaboration with the NSIDC and the WGMS, to continue the inventorying task with space-borne sensors as a logical extension of the WGI and storing the full complement of the WGMS-defined glacier characteristics (see Kääb et al. 2002, Bishop et al. 2004, Kargel et al. 2005). GLIMS is designed to monitor the world's glaciers primarily using data from optical satellite instruments, such as the *Advanced Spaceborne Thermal Emission and reflection Radiometer* (ASTER), an instrument that is required on board of Terra satellite (Box 3.2). A geographic infor-

Box 3.1 Online data access to the WGI and GLIMS databases

The ***World Glacier Inventory* (WGI)** currently has detailed information on over 100 000 glaciers throughout the world. Parameters within the inventory include coordinates (latitude and longitude) per glacier, together with tabular information about geographic location, area, length, orientation and elevation, as well as classifications of morphological type and moraines. The entire database can be searched by entering attributes and geographical location. The data sets thus selected or the entire database can be downloaded via the websites of the NSIDC, the WGMS, or of the *GLIMS glacier database.*

The ***GLIMS Glacier Database*** stores some 62 000 digital glacier outlines together with tabular information such as glacier area, length and elevation. The database can be queried using a text or mapping search interface. Glacier outlines with the related information can be downloaded from the GLIMS website in several formats used by geographic information system software products.

WGI at NSIDC: http://nsidc.org/data/glacier_inventory/index.html
WGI at WGMS: http://www.wgms.ch/wgi.html
GLIMS Glacier Database: http://glims.colorado.edu/glacierdata/

Box 3.2 ASTER satellite images

Satellite data are an important resource for global-scale glacier monitoring. They enable the observation of land ice masses over large spatial scales using a globally uniform set of data and methods, and independent of monitoring obstacles on the ground such as access problems and financial limitations on institutional levels. On the other hand, space-aided glacier monitoring relies on a small number of space agencies, the financial resources and political willingness of which are thus crucial for the maintenance of the monitoring system. Typical glaciological parameters that can be observed from space are glacier areas and their changes over time, snow lines, glacier topography and glacier thickness changes, and glacier flow and its changes over time (Kääb 2005).

The satellite images in this publication were taken by the *US/Japan Advanced Thermal Emission and Reflection Radiometer* (ASTER) onboard the *NASA Terra* spacecraft. They were acquired within the *Global Land Ice Measurements from Space* (GLIMS) initiative and obtained through the *US Geological Survey/NASA EOS* data gateway. The ASTER sensor includes two spectral bands in the visible range (green and red), one band in the near-infrared, six bands in the short-wave infrared, and five bands in the thermal infrared. The most important bands for glaciological applications are the visible, near- and short-wave infrared bands (Fig. 3.1 a–d). They allow for automatic mapping of ice and snow areas. This technique exploits the large difference in ice and snow reflectivity between the visible, near- and short-wave infrared spectrum, and enables the fast compilation of a large number of glacier outlines and their changes over time. In addition to the above-mentioned nadir bands, ASTER has also a back-looking stereo sensor that, together with the corresponding nadir image, allows for the photogrammetric computation of glacier topography and its changes over time (Kääb 2005).

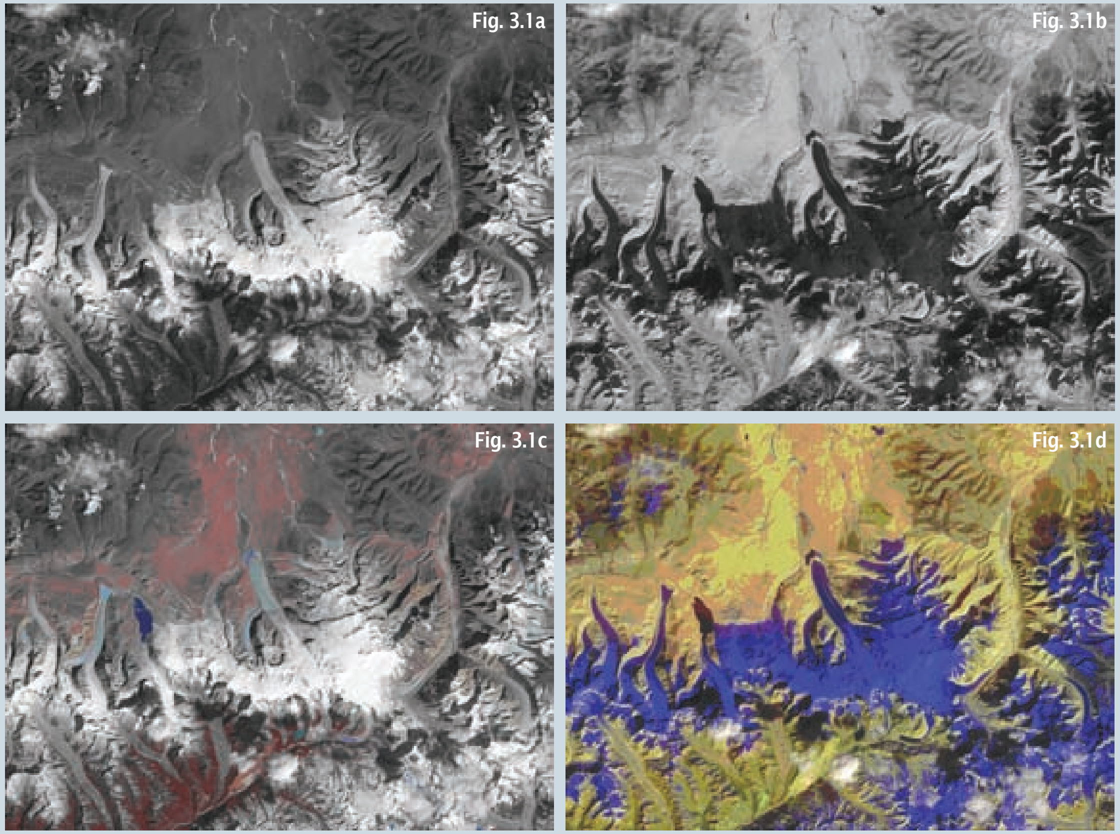

Fig. 3.1 a—d Glaciers in Bhutan, Himalayas (57x42 km): a) green ASTER band, b) shortwave-infrared, c) colour composite of the green, red and near-infrared bands, and d) colour composite of red, near-infrared and short-wave infrared bands.

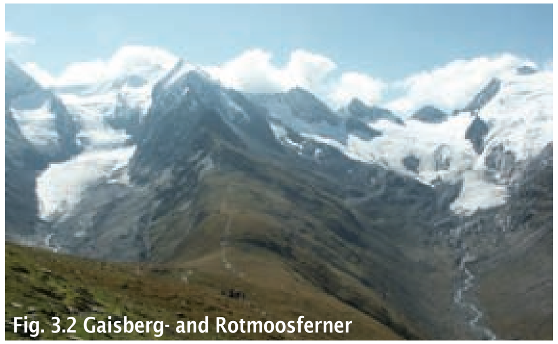
Fig. 3.2 Gaisberg- and Rotmoosferner


Fig. 3.3 Piedmont glaciers

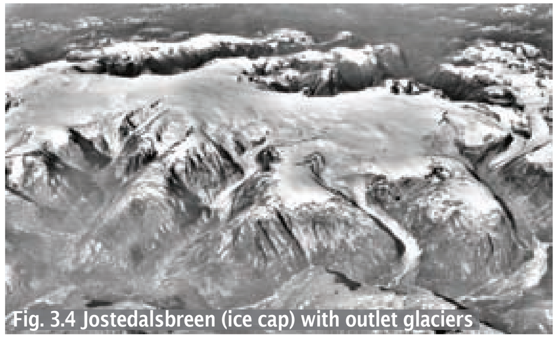
Fig. 3.4 Jostedalsbreen (ice cap) with outlet glaciers

mation system, including database and web interfaces, has been designed and implemented at the NSIDC in order to host and distribute the information from the WGI and the new GLIMS databases (Raup et al. 2007). In addition to the point information of the WGI, the GLIMS database now contains digital outlines on over 62 000 glaciers (status as of May, 2008). A global overview of the distribution of glaciers and ice caps as well as available datasets is given in Figure 3.6. New projects, such as the *International Polar Year* (IPY; www.ipy.org) and the *GlobGlacier* project, a data user element activity within the *European Space Agency* (Volden 2007), aim at making a major contribution to the current WGMS and GLIMS databases.

At first glance it might be surprising to find that after more than three decades of cryosphere observation from space (see IGOS 2007) there is still no complete detailed inventory of the world's glaciers and ice caps. Glacier mapping techniques from threshold ratio satellite images have been developed and automated to a high degree (Paul et al. 2002). However, fully automated inventorying of individual glaciers is hampered by challenges encountered with topographic shadowing effects, debris-covered and calving glaciers, clouds and snow separation as well as with the location of ice divides. A high quality inventory of glaciers and ice caps from both aerial photographs and satellite images still needs to be operated by a well-trained glaciologist. Empirical values of completed glacier inventories based on satellite images (e.g., Paul and Kääb 2005), indicate average operation times of five minutes per glacier for the semi-automatic detection of ice outlines as well as manual correction of errors due to shading and debris cover, and another five minutes per glacier for the delineation of individual glacier catchments, neither including the compilation of useful satellite images nor the rectification and restoration of the scenes (see Lillesand and Kiefer 1994)

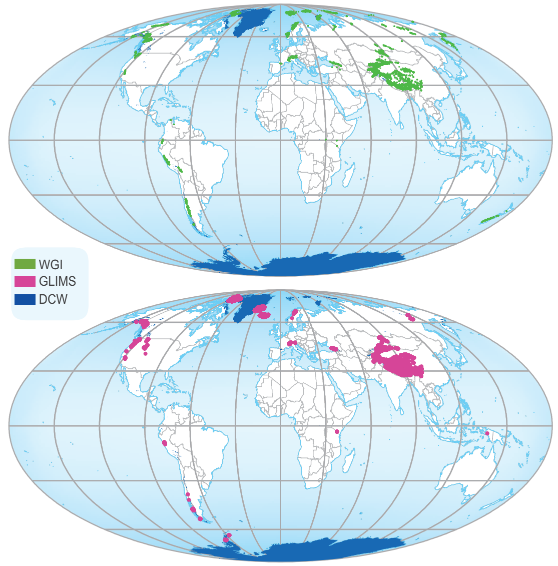

Fig. 3.6 Global glacier inventories

estimates of the ice cover of glaciers and ice caps, surrounding the continental ice sheets, are 70 000 km^2 in Greenland based on Weidick and Morris (1998) and ranges between 70 000 km^2 (Weidick and Morris 1998) and 169 000 km^2 (Shumsky 1969) for Antarctica. Hence the values indicated in the table (Table 3.1) of the IPCC report (2007), represent minimum values of the global area of glaciers and ice caps as well as their potential contribution to sea level rise.

Table 3.1 Ice sheets, ice shelves, glaciers and ice caps

Cryospheric Component	Area (mio km^2)	Ice volume (mio km^3)	Potential sea level rise (m) [e]
Glaciers and ice caps			
- smallest estimate [a]	0.51	0.05	0.15
- largest estimate [b]	0.54	0.13	0.37
Ice shelves [c]	1.50	0.70	~0
Ice sheets			
- Greenland [d]	1.7	2.9	7.3
- Antarctica [c]	12.3	24.7	56.6

Notes:
[a] Ohmura (2004); glaciers and ice caps surrounding Greenland and Antarctica are excluded; [b] Dyurgerov and Meier (2005); glaciers and ice caps surrounding Greenland and Antarctica are excluded; [c] Lythe et al. (2001); [d] Bamber et al. (2001); [e] Assuming an oceanic area of 3.62 × 100 mio km^2, an ice density of 917 kg/m^3, a seawater density of 1 028 kg/m^3, and seawater replacing grounded ice below sea level.

Source: IPCC (2007), Table 4.1

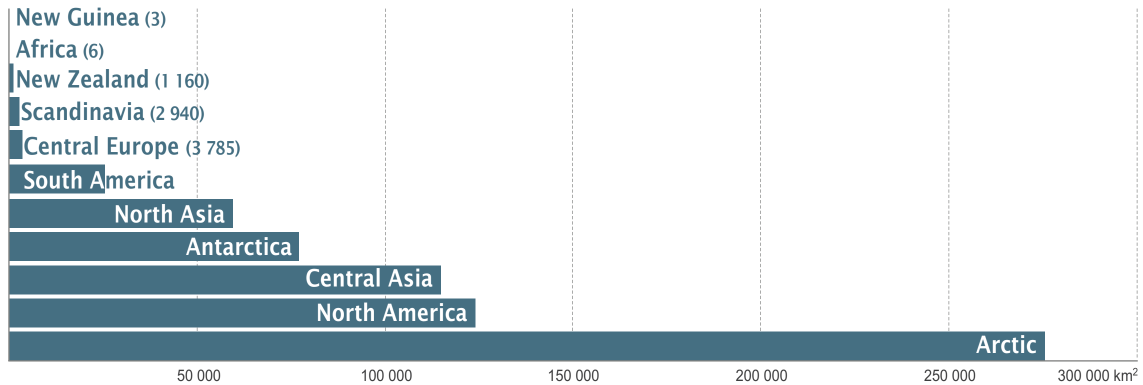

Fig. 3.7 Regional overview of the distribution of glaciers and ice caps

Fig. 3.6 Worldwide distribution of perennial surface ice on land. The map shows the approximate distribution of glaciers, ice caps and the two ice sheets from ESRI's Digital Chart of the World (DCW), overlaid by the point layer of the *World Glacier Inventory* (WGI) and the polygons of the *Global Land Ice Measurements from Space* (GLIMS) databases (status June 2008).

Fig. 3.7 Regional overview of the distribution of glaciers and ice caps. Source: Dyurgerov and Meier (2005).

Table 3.1 Area, volume and sea level equivalent of glaciers and ice caps, ice shelves and the two continental ice sheets as given in the latest report of the Intergovernmental Panel on Climate Change. The values for glaciers and ice caps denote the smallest and largest estimates, excluding the ice bodies surrounding the ice sheets on Greenland and Antarctica. Source: IPCC (2007), Table 4.1