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GLACIERS AND THE ENVIRONMENT

United Nations Environment Programme
Glaciers and the Environment
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(UNEP/GEMS Environment Library No 9)

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3. The African Elephant
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5. Food Contamination
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GLACIERS AND THE ENVIRONMENT

The UNEP/GEMS Environment Library

Earthwatch was the name given in 1972 by the UN Conference on the Human Environment to the assessment activities included in its action plan. Under the plan, each UN agency monitors and assesses those aspects of the environment that fall within its mandate. This Global Environment Monitoring System (GEMS) was formally created two years later, in 1974, and the system is coordinated by the United Nations Environment Programme (UNEP) and its partner agencies through a Programme Activity Centre at UNEP's Nairobi headquarters.

GEMS now has more than 15 years of solid achievement behind it. In that time, it has helped make major environmental assessments of such things as the impact of global warming, the pollution of urban air, the rate of degradation of tropical forests and the numbers of threatened species—including the African elephant—in the world.

As is proper, the results of these assessments have been regularly published as technical documents. Many are now also published, in a form that can be easily understood by those without technical qualifications, in the UNEP/GEMS Environment Library.

This is the ninth volume in the series, and is a somewhat unusual one. It deals with glaciers which, unlike the African elephant or urban air pollution, for example, have not recently been the subject of concerned public debate.

Why glaciers? Firstly, because glacier monitoring is, rightly, an important part of GEMS activities. Glaciers are important to the environmental health of the planet, playing subtle roles in the regulation of the Earth's heat balance. They also act as some of the most sensitive instruments we have for measuring climatic change and for recording a frozen history of the composition of the atmosphere and of precipitation back through the ages.

Finally, and again unusually for this series, I also commend this publication to you purely for the fascination of the science that it contains.

Michael D. Gwynne
Director, Earthwatch and GEMS, and
Assistant Executive Director Environment
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Environment Programme

Michael D. Gwynne

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Cold polar glaciers on Axel Heiberg Island near the Arctic Circle in Canada's Northwest Territories.

(Cover photo: J. Alean)

Foreword

Mostafa K. Tolba

It is difficult to believe—in these times of global warming and recurrent drought—that the Earth is essentially a glacial planet. Over millennia there have been numerous Ice Ages, the latest of which started to end a mere 20 000 years ago. It takes a global temperature decrease of only 6 °C to revert large expanses of central Europe and Asia to permafrost. Ten percent of the Earth's surface—some 15 million km^2—is currently covered by glaciers. There are glacierized regions or mountainous icecaps in every continent of the world, even on the equator.

What use glaciers? These great, implacable frozen masses of ice and snow remind us of our place in time and space, and have valuable uses, vital to the daily lives of millions of people. The information they have trapped in their frozen interiors may also be critical to human development and survival.

Seventy-five percent of the world's freshwater is stored in glaciers, and the water they release is used to produce hydropower and for irrigation. Glaciology—the scientific study of snow and ice—is catalysing the development of early-warning systems for some glacier-related natural disasters such as ice avalanches. Furthermore, glaciers provide a frozen record of atmospheric conditions over long periods of time. Ice cores from glaciers have been used to establish, for example, the levels of carbon dioxide and other chemicals in the atmosphere in pre-industrial times. Finally, glaciers can provide indications of climatic change in the past and of changes occurring at present.

The retreat of glaciers worldwide during the past century is evidence of global climate change that can be easily understood by everyone, and it is important that we recognize, document and study this important signal of climate change. Systematic worldwide observation of glaciers started in 1894. In 1976 a worldwide inventory of glaciers and ice sheets was begun, the first report of which—*World Glacier Inventory: status 1988*—was published in 1989. Glacier monitoring is now coordinated by the World Glacier Monitoring Service, established in 1986 with help from UNEP and other national and international bodies.

The aim of this publication is to make the knowledge we have gained about glaciers more widely known, and to emphasize the need to develop this knowledge. Glaciology holds one of the keys to our past. It may also hold many to our future.

Mostafa K. Tolba
Executive Director
United Nations Environment Programme

Overview

There have been two Ice Ages over the past 150 000 years, and a long interglacial period which lasted from about 125 000 to 75 000 years ago. We are currently enjoying another interglacial period—one that this time may be intensified far beyond natural ranges as a result of global warming caused by the accumulation of greenhouse gases in the atmosphere. Indeed, it is possible that this global warming could be greater than any of the temperature fluctuations undergone during the transition from an Ice Age to an interglacial period.

Yet much of the Earth— which can justly be referred to as a glacial planet—is blanketed in ice and snow, even during interglacial periods. During winter in the northern hemisphere, ice and snow cover half the world's land area and some 30 percent of the oceans. About 10 percent of the land area is covered with glaciers, which contain 75 percent of the world's freshwater resources. Most of this is stored in the huge ice sheets of Greenland and Antarctica. The remaining glaciers and mountainous ice caps cover an area of some 550 000 km^2, nearly all of it in North America and Eurasia.

Glaciers can be regarded as the residual remains of the large ice bodies of the past Ice Age—or as the precursors of the ice sheets of the next Ice Age. And just as the sizes of the massive ice sheets that characterize Ice Ages are a crude indicator of climatic and environmental change, so are the planet's glaciers a sensitive instrument for measuring more subtle changes over shorter timeframes.

During winter in the northern hemisphere, ice and snow cover half the world's land area and some 30 percent of the oceans.

Because the ice in glaciers is near melting point, glaciers act as sensitive indicators of climate change. The spectacular and worldwide retreat of mountain glaciers this century is the strongest evidence so far of the fact that the Earth's average surface temperature has changed significantly and rapidly since the Little Ice Age ended in the last century.

Glaciers are of great scientific interest in their own right but their study also has practical importance in many fields. As ice accumulates over thousands of years it provides a record, in cold storage, of the atmospheric conditions prevailing when the ice was formed. It was a study of ice cores that enabled scientists to establish background levels of carbon dioxide and other chemicals in the atmosphere before industrialization began.

The study of glaciers is also important in the design of hydroelectric schemes, since it is often the water released

H. J. Zumbühl

A 19th century print showing an advancing glacier—the Upper Grindelwald Glacier in Switzerland—pressing against the timber line and agriculture. during the Little Ice Age. The painting was made by Thomas Fairnley in August 1835.

by glaciers that provides their power. Additionally, glaciers are implicated in the onset of flooding, avalanches and debris flows, and their advance and retreat can cause the formation and abrupt release of the contents of large lakes blocked by ice. Finally, the melting of glaciers is thought to have been responsible for roughly one-third of the 10- to 20-cm rise in sea level that has been observed over the past 100 years.

The systematic worldwide observation of glaciers began in earnest in 1894, with the creation of an International Glacier Commission. In 1976, with help from UNESCO's International Hydrological Programme (IHP), a project to inventory the world's glaciers and ice sheets was begun. A first report was issued in 1988; glacier monitoring is now coordinated by the World Glacier Monitoring Service, supported by the Global Environment Monitoring System (GEMS, UNEP), IHP and the International Association of Scientific Hydrology.

The spectacular and worldwide retreat of mountain glaciers this century is the strongest evidence so far of the fact that the Earth's average surface temperature has changed significantly and rapidly since the Little Ice Age ended in the last century.

The background

The history of ice

A few million years ago, as the Antarctic continent migrated towards the South Pole and began to build up a large ice sheet, conditions became ripe for the onset of the modern Ice Ages. The seas cooled as ice flowed into the sea from the Antarctic ice sheet, air temperatures fell and the climate eventually became sensitive to periodic variations in solar radiation caused by fluctuations in the Earth's orbit round the Sun. Continental ice sheets began to form and their whiteness reduced the amount of solar radiation absorbed by the Earth, accentuating the cooling still further.

During an Ice Age, the land becomes depressed by the weight of ice that covers it. Land levels fall, generally by about one-third of the thickness of ice that covers the land. At the same time, ice sheets trap much of the available moisture in frozen form, and sea levels fall. The evidence suggests that sea levels fall by 100 to 140 metres during an Ice Age.

There is no agreed view on how many Ice Ages occurred during the past two million years. It is clear, however, that they were separated by a number of much warmer, interglacial periods. As the ice melts at the end of an Ice Age, the land begins to rise again, quickly to begin with and more slowly later on. During the initial ice melt, land levels can rise as much as 9 metres a century but the whole process takes a long time—at least 20 000 years. Although the last Ice Age started to end some 20 000 years ago, land at the head of the Gulf of Bothnia is still rising by 90 cm a century, and the Stockholm archipelago is rising by 50 cm a century.

The Earth's climatic history is better understood from about 75 000 years ago when the first of two Ice Ages—Wisconsin I and Wisconsin II—set in. Wisconsin II reached its coldest about 20 000 years ago (see Figure 1). At that time, the largest ice sheet, the Laurentide, was still covering the northern part of North America, and other ice sheets lay over Scandinavia, the British Isles and Eastern Siberia in the northern hemisphere (see Figure 2) and over Patagonia and Tierra del Fuego in the southern hemisphere. Although the average temperature of the Earth's surface was only some 6 °C cooler than now, the ground was permanently frozen in central Europe and much of Asia. The sea level fell more than 100 metres, the Bering Strait dried up, and early man was able to hunt mammoths not only in Eurasia but in what later became known as the New World.

The build-up of large ice sheets caused complex meteorological changes, notably the deflection of winds from the Pacific around the northern edge of the

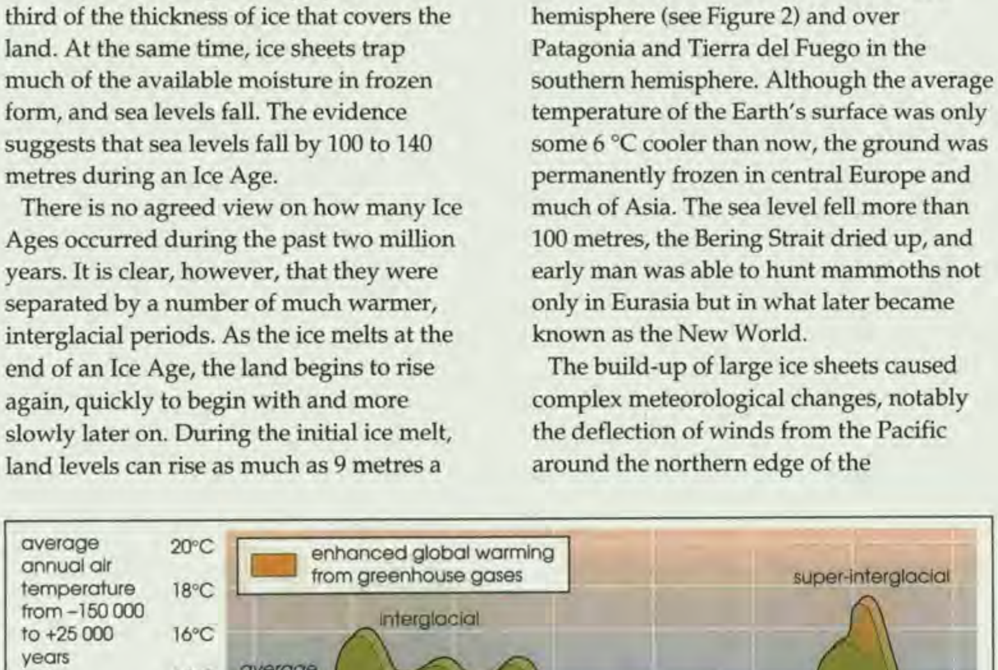

Figure 1 shows the sequence of ice ages over the past 150 000 years, and a projection for the next 25 000 years. The current interglacial period is likely to become a superinterglacial period intensified by an enhanced greenhouse effect.

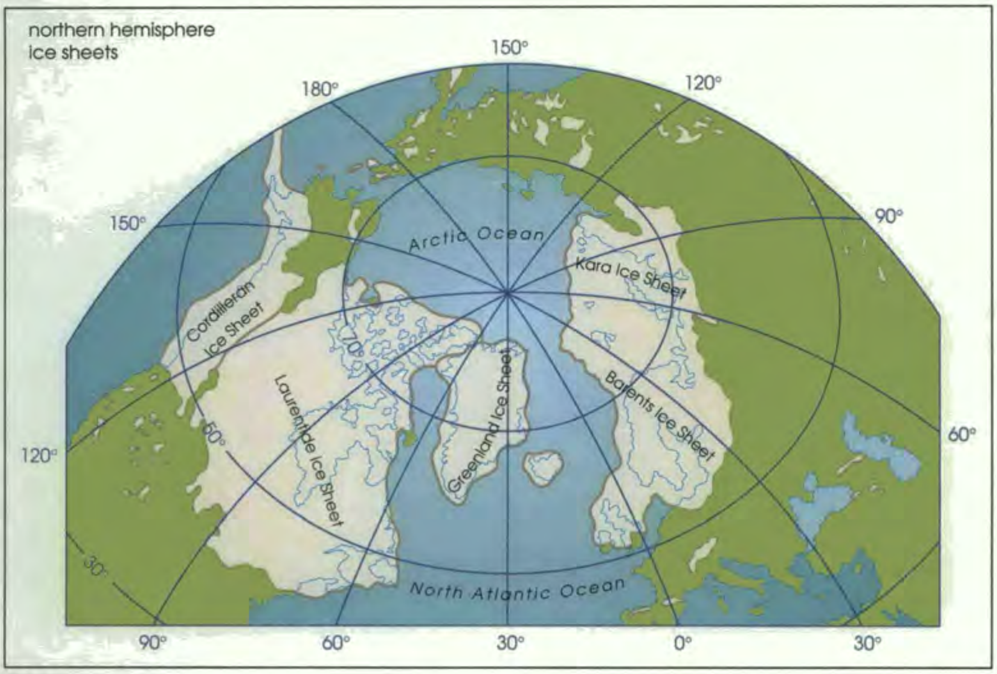

Figure 2 Extent of ice sheets in the northern hemisphere during the past Ice Age. Sea levels were lowered by 100 metres or so as moisture became locked up in ice sheets.

Laurentide. These cold winds cooled the Atlantic, and ice cover spread further south, as far as the Pyrenees. The Eurasian ice sheets were then denied the Atlantic as a source of their moisture, and the Alpine glaciers thinned and froze to their beds. This was the time of the cold desert. As precipitation dropped, glaciers and ice sheets began to lose mass, snow and ice cover began to retreat, and the frozen ground began to absorb more solar radiation. Within a few thousand years, the ice cover had gone and global warming had set in, accompanied by a sharp increase in the levels of greenhouse gases in the atmosphere. This was a catastrophic period of climate change, which resulted in the extinction of many large mammals.

By about 10 000 years ago, average global temperature and precipitation were similar to those of today. Many mountain glaciers far away from the remaining ice sheets were as small as now, though cold periods—such as the Little Ice Age that gripped the land from about the early 17th to the mid-19th century—occurred repeatedly, lengthening and swelling the glaciers once again. Since the mid-19th century both the length and mass of glaciers worldwide have been shrinking—probably at a faster rate than at the end of the past Ice Age. While this is presumably a natural phenomenon, it is also possible that an enhanced greenhouse effect could be partly responsible. If we fail to prevent an enhanced greenhouse effect a super-interglacial period with a warmer climate may occur during the coming centuries, with temperatures perhaps warmer than any experienced for millions of years. Some 10 000 or 20 000 years after that, the climate may shift again towards another Ice Age.

The nature of glaciers

Glacierized areas (km^2)

South America	25 908
North America	276 100
Greenland	1 726 400
Europe	53 967
Asia and CIS	185 211
New Zealand/ sub-Antarctic islands	7860
Antarctica	13 586 310
TOTAL	15 861 766

Glacier ice currently covers 10 percent of the Earth's surface, or some 15 million km^2. Although this resource contains 75 percent of the world's freshwater, most of it is stored far away from human habitat and action, in the massive ice sheets of Greenland and Antarctica.

The remaining 3–4 percent of ice is found spread over an area of 550 000 km^2 as glaciers and on mountainous ice caps. Of this total, 50 percent is found in North America, 44 percent in Eurasia, 5 percent in South America and 1 percent in New Zealand. In most of these areas, glaciers are of considerable economic importance as a result of the water they provide for hydroelectric schemes and irrigation.

Glaciers are basically moving bodies of snow and of ice that has been formed as a result of the recrystallization of snow. The snow falls high up on the glacier, becomes compressed under subsequent layers of snow, turns first to a heavier but still porous intermediate material called firn, and finally turns to ice. All the while, the snow, firn and ice of which the glacier is composed move downhill, from colder areas to warmer ones.

At the top of a glacier more snow falls than disappears through melting, run-off and evaporation. At the bottom, the reverse is true. It follows that somewhere in the middle of the glacier there is an equilibrium line, where snowfall equals snow loss. The area above the equilibrium line is called the accumulation area, and that below it the ablation area. The surface of the accumulation area is composed mainly of snow, while that of the ablation area is mainly of ice (see Figure 3).

There are two main types of glacier: maritime and continental. Maritime glaciers are characterized by heavy precipitation (more than 2000 mm a year), mean annual air temperatures close to freezing point, and low-altitude equilibrium lines near or below the timber line. Because of the heavy snowfall they experience, these glaciers flow rapidly. They include temperate ice caps in Patagonia, Iceland and Norway, networks of large temperate glaciers, particularly in the coastal mountains bordering the Gulf of Alaska, and temperate mountain glaciers in the Caucasus, the outer Alps and on Kenai Peninsula in Alaska.

Continental glaciers are found where precipitation is less than about 500 mm a year. Their equilibrium line retreats far above alpine meadows and into regions of permafrost where the mean annual air temperature is less than about –8 °C. These

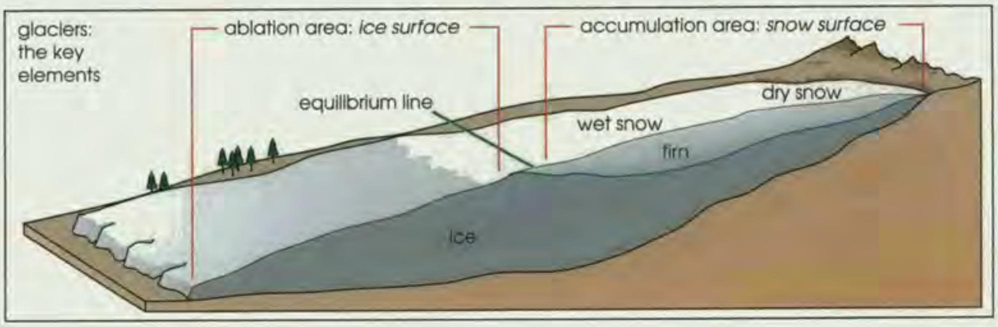

Figure 3 Main elements of a typical glacier in a steady-state situation

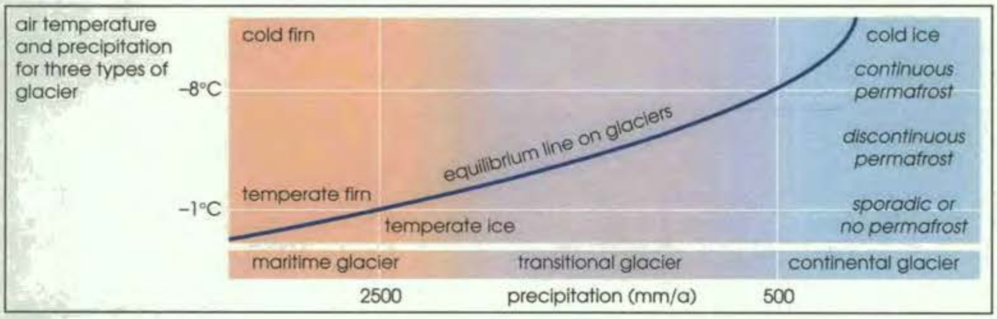

Figure 4 The relationship between precipitation and average annual air temperature determines the nature of a glacier: maritime, transitional or continental.

glaciers flow slowly, and are found mainly in the polar regions and in the driest parts of the Asian mountains.

There is also a third type of glacier with characteristics midway between these extremes. These transitional glaciers are found where precipitation is between 500 and 2000 mm a year, and average temperatures are a few degrees below freezing point. They are common in Svalbard, the Argentinian Andes, the inner Alps and most mountain ranges in Asia. The relationship between these three types of glacier, average air temperature and precipitation is shown in Figure 4. The photographs below show typical examples of maritime, transitional and continental glaciers.

Three types of glacier: maritime mountain (Portage, in southern Alaska, below left); transitional (Svalbard, in the Arctic north of Scandinavia, below); and continental (Urumqi in China, bottom).


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The behaviour of glaciers

The making of a glacier

Glaciers are formed in areas where more snow falls in the winter than melts or evaporates in the summer. Glacier movement transfers this excess snow (and ice formed from it) from the accumulation area on the upper part of the glacier to the ablation area, where melting predominates, on the glacier's lower part.

Fresh snow has a density of 100 kg/m^3 or less. When it becomes compressed by substantial accumulations of snow above it, fragile snow crystals are transformed into spherical particles. As these pack closer and closer together, density reaches some 500 kg/m^3 after a year or more, creating a porous material known as firn.

If such conditions prevail year after year, increasing pressure gives rise to larger crystals and higher densities. When the density reaches 830 kg/m^3, the crystals join together and the air between them becomes trapped as bubbles. This material is impermeable, is milky or even brilliantly white because of the air trapped in it, and is called glacier ice.

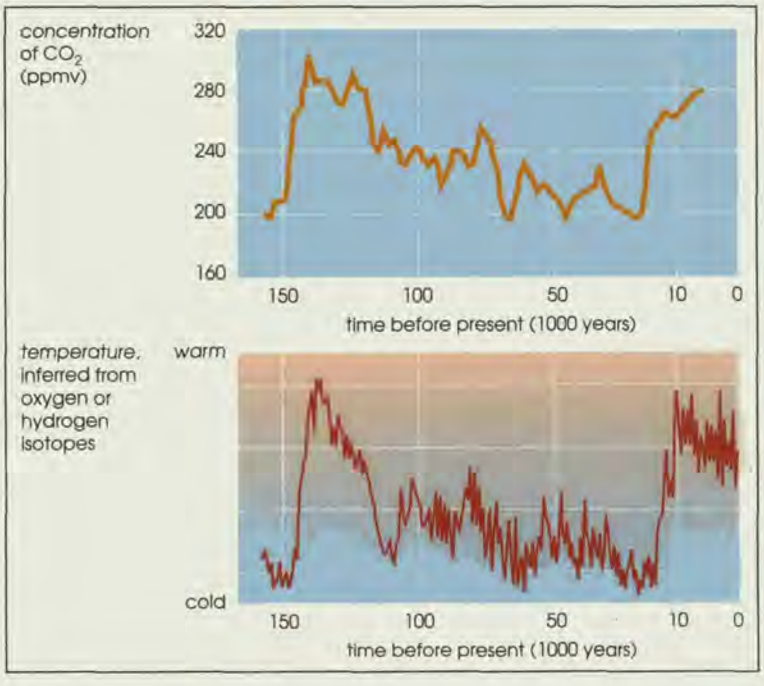
In Greenland and Antarctica, this process occurs at temperatures of –20 °C or less, takes a century or more, and happens 50 or 100 metres below the snow surface. The ice and air bubbles that have been trapped in glaciers provide a frozen archive of the composition of the atmosphere and the nature of precipitation many years ago. Ice cores from glaciers have also revolutionized our knowledge of earlier climates.

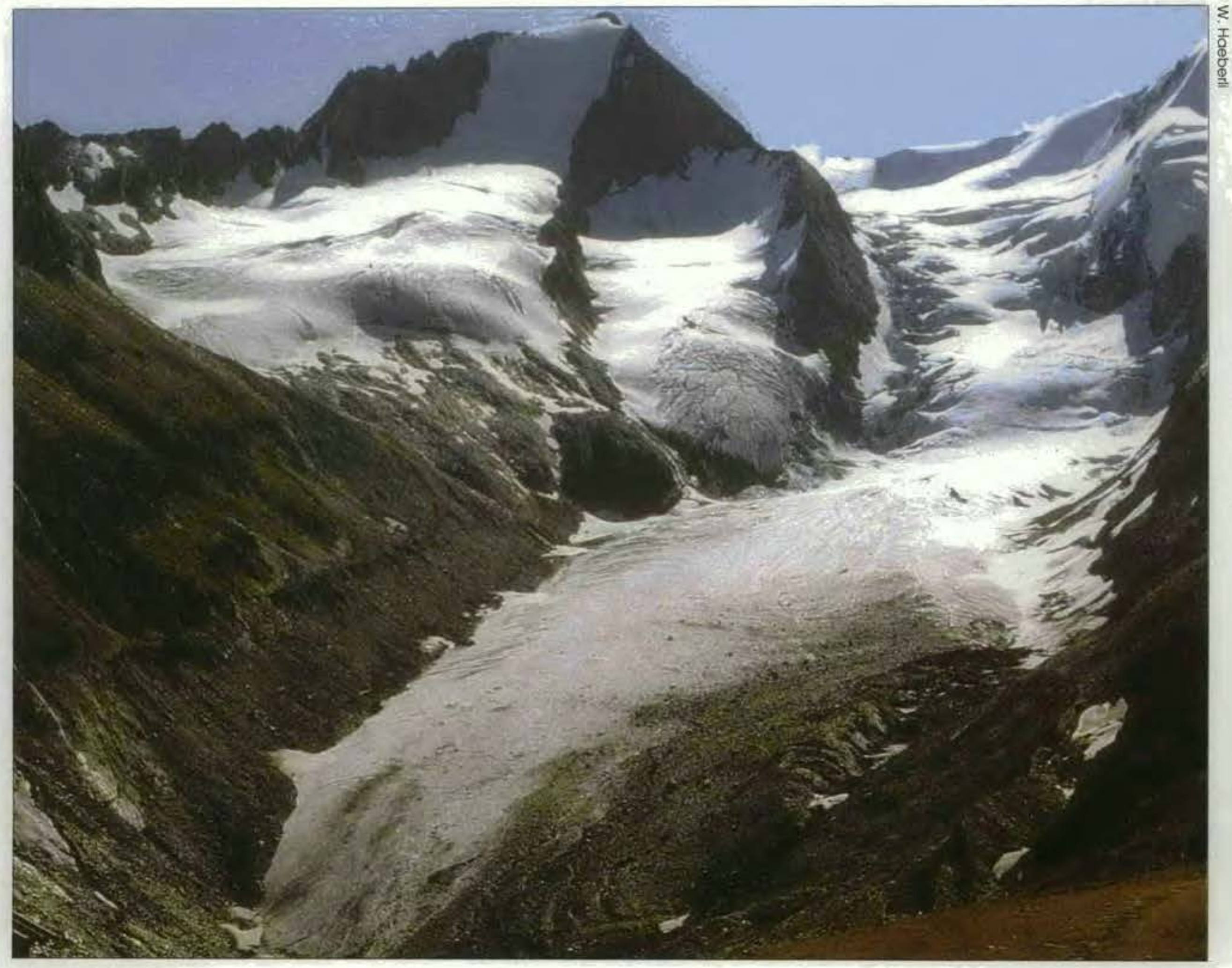
The longest ice core thoroughly analysed so far is from Vostok in Antarctica, with a length of 2521 metres and spanning 160 000 years. It provided a fascinating picture of the fluctuations of carbon dioxide (CO_2) in the atmosphere before and during the last Ice Age, as well as during the past 10 000, more temperate years. Drilling by American and European scientists in Greenland has been going on since 1989, and researchers there hope to reach even older ice.

The Vostok research showed that the concentration of CO_2 in the atmosphere and atmospheric temperature (as recorded by the ratio of hydrogen and oxygen isotopes) changed almost perfectly in step with one another during the past two Ice Ages and during the interglacial period that separated them (see Figure 5).

Ice core analysis also helped establish baseline levels for CO_2, which became badly needed as concern over greenhouse warming mounted during the 1970s and 1980s. A baseline pre-industrial value of 270–290 parts per million (ppm) was established by several methods, and this was later refined to 260 ppm as a result of the analysis of ice cores.

Figure 5 Analysis of ice cores shows that CO_2 concentration in the atmosphere and air temperature (as revealed by oxygen or hydrogen isotopes) moved closely in step with one another over the past two Ice Ages.





W. Haeberli

In glacierized areas where there is some melting during the summer, small amounts of meltwater can infiltrate the snow layer that fell earlier in the year. This meltwater then refreezes, leaving a distinctive trace of warmer summers which will remain hidden deep below the surface after centuries of snowfall have covered it up. The amount of refrozen melt layers in a core taken from such a glacier is a reliable guide to summer temperatures. As Figure 6 shows, analysis of an ice core taken from Devon Island in the Arctic shows that the 20th century must have been by far the warmest century since the Middle Ages. Similarly, analysis of ice cores on Colle Gnifetti in the Swiss Alps has revealed the rise of acid precipitation since the middle of the last century (see Figure 7).

The way in which a glacier builds up through accumulation is relatively simple: it is governed mainly by the amount of snow that falls on the head of the glacier.

Ablation is more complicated. The intensity of melting caused by solar radiation depends on the reflectivity of the material exposed on the glacier surface, since only absorbed—not reflected—radiation contributes to heating. Fresh snow reflects 80–95 percent of solar radiation, old snow 50–80 percent, firn 30–60 percent and ice 15–40 percent. These figures illustrate the importance of summer snowfall in protecting glaciers from ablation.

Radiation contributes about two-thirds of the energy available for melting. The remaining third comes mainly from heating by the atmosphere as warm air is convected onto the glacier surface. The rate of melting depends largely on the air temperature above the glacier and hence

Gaissbergferner in the Oetztal Alps, Austria: the exposed lateral moraines clearly indicate 20th-century mass loss.

Sketch below shows the Rhône glacier in 1856.

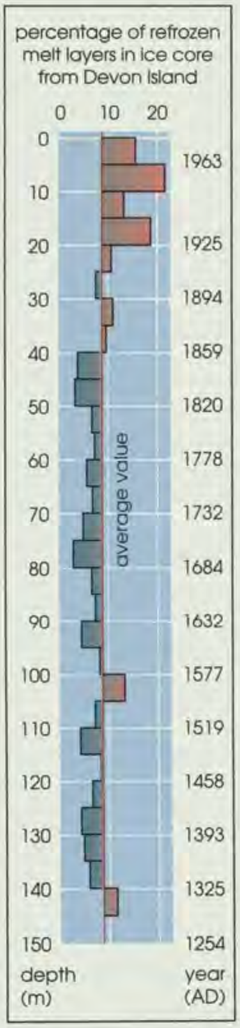


Figure 6 Percentage of refrozen melt layers above or below average in an ice core from Devon Island in the Arctic shows that the 20th century must have been by far the warmest century since the Middle Ages.

convection causes less melting on glaciers at high altitudes and latitudes than at low ones. Some reduction in glacier mass is also caused by the evaporation of snow, firn and ice when humidity is low.

An understanding of the factors responsible for accumulation and ablation in glaciers enabled scientists to make a number of useful deductions about glacier behaviour in the first half of this century. Although solar radiation is the most important process quantitatively, the intensity of solar radiation varies little from year to year compared to the variations that occur in precipitation and air temperature. It was therefore concluded that precipitation rates alone could be used to estimate accumulation rates, and air temperature alone could be used to estimate ablation rates.

One practical result of this work is that hydrologists can use records of air temperature to estimate the rate at which glaciers are melting and so supplying water to, for example, a hydroelectric plant. Another concerns the position of the equilibrium line on a glacier, the point at which the accumulation rate equals the ablation rate. Meteorologists argued that since accumulation must equal ablation along the equilibrium line, the air temperature there can be used to predict precipitation rates. The glacier itself can thus be used as a kind of giant precipitation gauge, providing meteorologists with information that it would be hard to obtain in any other way—precipitation rates are difficult to measure high up on remote and cold glaciers.

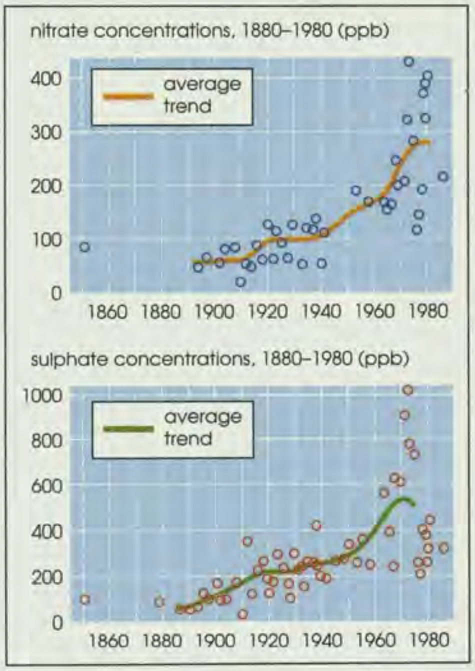


Figure 7 Concentrations of nitrate and sulphate ions in ice core samples taken from Colle Gnifetti in the Swiss Alps chart the rise of acid precipitation.

A reduction in snow cover can amplify temperature changes, turning the areas of glaciers above the equilibrium line into sensitive climatic indicators. The mechanism involved is simply that if a small rise in temperature occurs, the area of snow cover will decrease. More dark ground will be exposed, the reflectivity of the area will fall, and more solar radiation will be absorbed in areas adjacent to the glacier. This will increase the rate of ice melt, establishing a feedback mechanism in which a small change in temperature results in a large change in ice and snow cover. Glaciers in polar regions are less sensitive to warming because meltwater tends to refreeze, but feedbacks will enhance the effect of global warming.

Taking a glacier's temperature

Most people regard freezing point as cold. Not so glaciologists, who describe glaciers in which the main body of snow, firn and ice is at 0 °C as temperate, and reserve the word cold for cooler glaciers. Glaciers that contain some material at 0 °C and some colder are called polythermal.

Glacier temperatures are measured by lowering probes down boreholes. Such measurements reveal that glacier temperatures below about 10 metres are remarkably stable, and that seasonal variations of air temperature have little impact. The body of the glacier is insulated by snow in the accumulation area; in the ablation area, the surface is ice which cannot become warmer than 0 °C.

Temperatures in the firn of the accumulation area are higher in many glaciers than might be expected. This is because meltwater can run down through the firn and freeze; in doing so, it gives up its latent heat of condensation, warming the firn. This is why temperate firn is found even in glaciers where the average annual air temperature is as low as –10 °C.

In cold accumulation areas, where there is little meltwater, firn temperatures echo air temperatures—although they also increase gradually from 10 metres down to bedrock as a result of geothermal heat, the energy released by ice deformation and the friction generated by ice sliding over rock. Temperatures in the upper 200 metres of cold accumulation areas in polar glaciers show strong deviations, suggesting a rise in air temperature of 2–4 °C during 1900–50. The uppermost layers, however, show a cooling since 1950 which offsets about half the earlier warming (see Figure 8). The effects of the remarkably warm 1980s are now starting to affect the temperature profile below the critical 10 metre level which represents the limiting penetration depth of seasonal temperature variations.

Such polar measurements suggest that there has been a rise in average annual air temperature this century of 1–2 °C—considerably more than the world average of 0.5 °C. This confirms the results, found in climate models used to simulate greenhouse warming, that warming trends are strongly amplified in the sensitive polar areas.

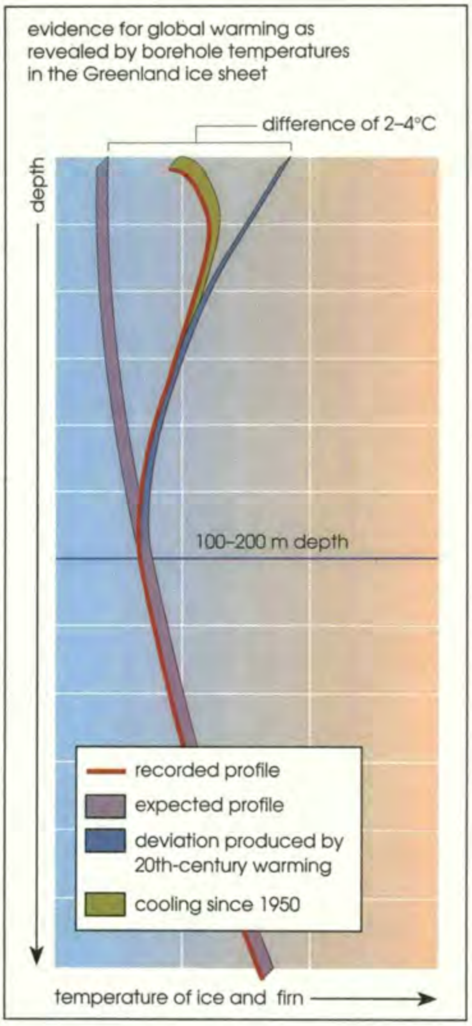


Figure 8 Temperature profiles from cold polar accumulation areas such as Greenland reveal both a 2–4 °C warming during this century, and a cooling since 1950 which offsets about half the warming. The effects of the warm 1980s are not yet apparent.

The glacier audit

Measuring whether glaciers are getting bigger or smaller, and by how much, is a complex and often exhausting business. Direct methods include digging pits through the snow and sinking boreholes into the ice, measuring the annual change in glacier depth at different altitudes, multiplying the average by the ablation or accumulation area, and arriving at an estimate of annual accumulation and ablation. The difference, known as the mass balance, is a measure of the mass of water the glacier as a whole is gaining or losing. Figure 9 shows a 38-year history of the Storbreen glacier in Norway derived using these techniques. Another technique involves creating a 'farm' of stakes over the glacier from which annual changes in depth can be measured from year to year.

Mapping or photographing the glacierized area, or even trying to calculate the difference between precipitation and run-off plus evaporation, are methods of obtaining a regional overview of changes in glacier size, but reveal less about the processes that bring these changes about.

The estimation of mass balance is an important part of any hydroelectric or irrigation scheme fed by glacier run-off. Glaciers have an interesting stabilizing effect on run-off: when the summer is moist and cool, and valley rivers are full, glaciers retain more water in frozen form; and when the summer is hot and dry, glaciers release more water to the parched regions below. Unfortunately, if global warming becomes pronounced, glaciers will contract, their stabilizing effect will be reduced, and summer water shortages in dry, lowland areas will be amplified. So may winter floods.

Glaciers are involved in many feedback mechanisms of this type. For example, global warming would lead inevitably to increased mass loss in glaciers, with the result that glaciers would become thinner and their surfaces less elevated. With the glacier surface at lower altitude, melting would increase, thus amplifying the glacier's response to global warming.

There is always a net loss of material at the glacier snout, where the mass balance is at its lowest. Mass balance rises to zero at the equilibrium line and reaches its maximum at the top of the glacier. The gradient of this change in mass balance at the equilibrium line is called the glacier's activity index.

A glacier's activity depends greatly on levels of precipitation—activity is high in areas of high precipitation, lower in dry areas. For example, the activity index of the South Cascade Glacier in western Washington is about 1–2 m per 100 m altitude increase. This high value results

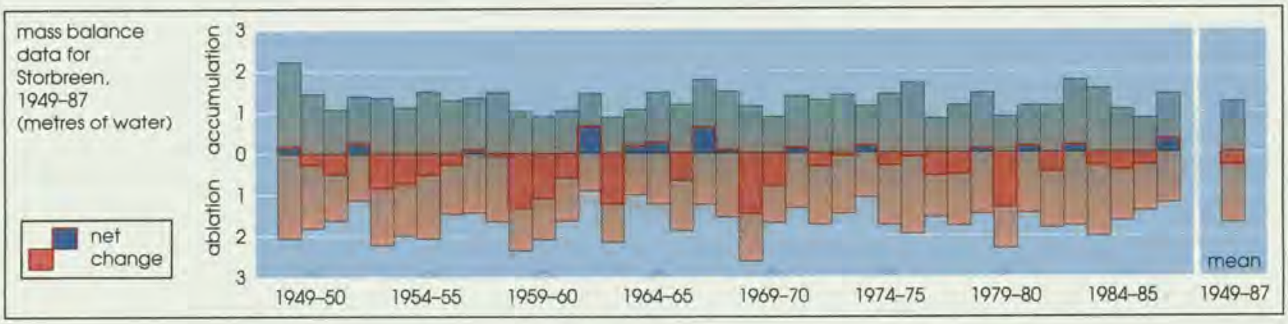


Figure 9 Mass balance measurements for Storbreen, a glacier in Norway, 1949–87. Mass loss has averaged a few tenths of a metre of water equivalent a year since the middle of the 20th century.

from a snow accumulation of about three metres a year. By contrast, glaciers situated high up in inland regions, where snowfall is much less, may have activity indices as low as 10 cm or less per metre.

The higher the index, the more will mass balance change in response to global warming. Glaciers in areas of high snowfall may therefore give us one of the first clues to the onset of warming, and today's glaciers will react more sensitively to warming than did glaciers in the drier atmosphere of the past Ice Age.

Mass balance measurements based on mapping carried out over the past century have already revealed the extent of loss in Alpine glaciers (see table). The annual mean mass balance for these glaciers is –40 cm, with a possible error of plus or minus 20 cm of water equivalent. Thus total glacier thinning over the past century has reached tens of metres. Much of this loss appears to have been in the first half century; from 1950 to 1970 there was a global cooling, when many glaciers maintained their mass. The 1980s were warmer—and their effects have been detected in recent studies of mass loss.

Mass balance measurements for Alpine glaciers

glacier	period	area (km^2)	elevation (metres)	mass balance (m/year)
Rhône	1882–1987	17.38	2940	–0.25
Vernagt	1889–1979	9.55	3228	–0.19
Guslar	1889–1979	3.01	3143	–0.26
Hintereis	1894–1979	9.70	3050	–0.41
North Schnee	1892–1979	0.39	2690	–0.35

How glaciers move

If glaciers did not move the accumulation area would mount ever higher and the ablation area would disappear altogether. That this does not happen is proof that, in a steady state, what is lost from the ablation area is compensated for by the movement of material downhill from the accumulation area. This also equals the amount of material that falls on the accumulation area.

Although glaciers usually move only slowly—typically a few tens of metres a year—the amount of material transported is massive. The movement consists of layers of snow, firn and ice moving over one another with increasing speed as they approach the equilibrium line. This acceleration serves to stretch and extend the glacier in the downhill direction, producing not only crevasses but also tending to bury the firn deeper within the glacier. In the ablation area, however, the ice begins to slow down and the force of deceleration attempts to compress the ice—with little success because ice is virtually incompressible. The ice is therefore forced to spread sideways towards the margins of the glacier, giving rise to the typical claw-shaped glacier tongue (see photo page 16).

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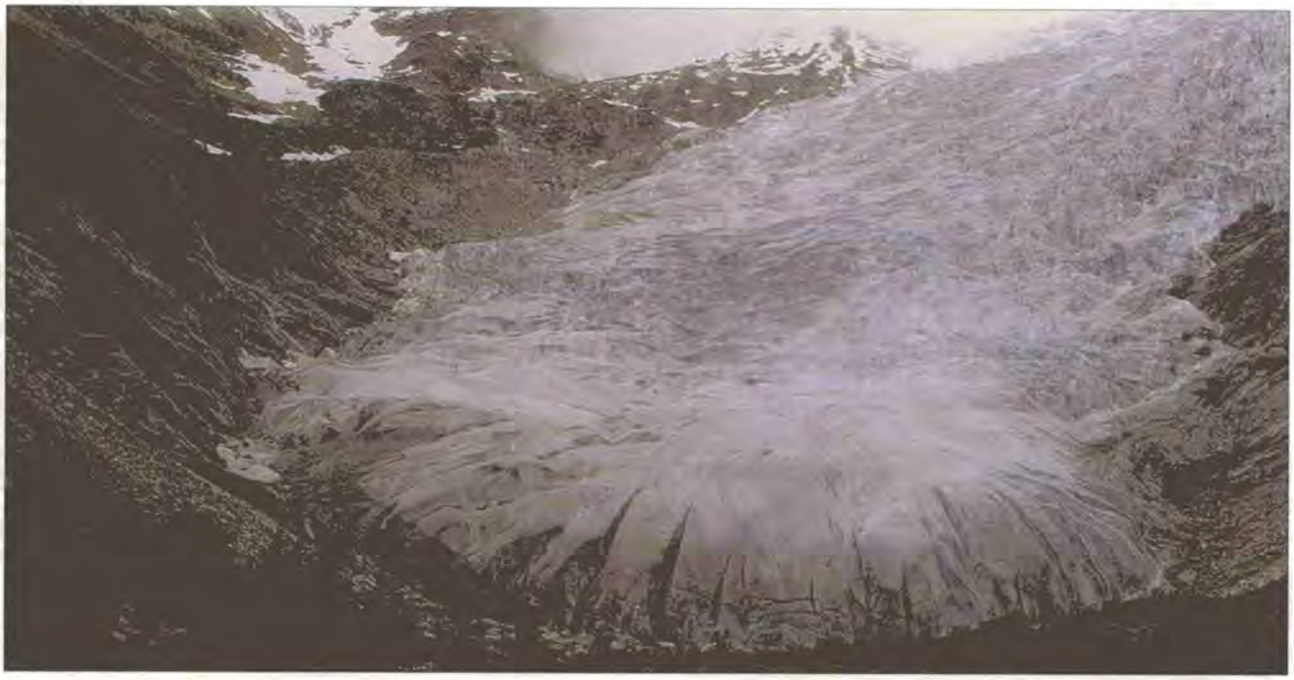
Photograph left shows scientists drilling through a glacier using a hot water jet.



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Typical animal claw glacier tongue (above) caused by compression forces generated by deceleration of the ice. Since ice is resistant to compression, it spreads sideways.

Material in the ablation area is also forced up towards the surface. The claw shape is reinforced by the fact that glaciers moving down steep slopes tend to be thin, and those moving down gentle slopes tend to be fat. As the glacier reaches flatter ground, it thus both thickens and spreads.

An unfortunate mountaineer falling into a crevasse in the accumulation area would therefore undergo some unexpected transformations. He would first be stretched and buried deeper until, in time, he crossed the equilibrium line. Decades or centuries later he would break surface again, doubtless somewhat distorted, near the glacier tongue. The 5000-year old body of a man was recently recovered from an Italian glacier on the Austrian border. The man had been buried under a ridge-top section of the glacier, and therefore had not travelled through it. However, the fact that he appeared at all confirms that Alpine glaciers are smaller today than at any other time during the past 5000 years.

The complexities of glacier flow have more useful characteristics than this. One is that the glaciologist can collect frozen precipitation from the past by walking up the ablation zone from the lowest point of the glacier, where the oldest ice of all appears at the surface having travelled from the uppermost point via the deepest parts of the glacier. The journey up-glacier reveals more and more recent surface ice until the equilibrium point is reached where recently formed ice stays on the surface. It follows that pre-industrial levels of the pollutants found in today's atmosphere are best defined from ice samples taken from glacier tongues in high mountain areas.

If the bottom of the glacier is at melting point, the glacier slides its way downhill against the bedrock. Its path is lubricated by meltwater running through the glacier's own internal drainage system. This drainage system serves important functions in the glacier but its channels can become blocked as a result of movement within the glacier. Drainage water may then become stored up in or behind the glacier. Eventually, such water will find a narrow path along which to escape. Should the escaping water be warm enough, it will then melt a larger conduit, allowing more water to flow which, in its turn, melts more ice and enlarges the conduit still further.

This is a recipe for potential catastrophe, since these events can happen quite swiftly, releasing extremely large volumes of water in a very short space of time. These glacier floods can be very destructive, sweeping large quantities of water and eroded moraine material rapidly downhill.

Glacier floods are often called by their Icelandic name, *jøkulhlaup,* since some of the most dramatic have occurred in that country. The 1922 Grimsvötn flood, for example, released an estimated 7.1 km^3 of water in a flood that delivered some 57 000 m^3 of water a second. The photograph below shows the results of a similar catastrophe in Münster in Switzerland in 1987.

Glacier flow involves two basic processes: the sliding of layers of ice over one another within the glacier, and the sliding of the glacier floor over rock. Where one can keep pace with the other, the glacier's behaviour is that of a steadily flowing river of ice. This peaceful image is shattered, however, when baserock sliding becomes the dominant force. Two forms of instability can then set in: the surge and calving instability, both intensively investigated in Alaska where they occur frequently.

A glacier surge happens after decades in which glacier material has built up; it usually lasts a few months to a year or more, during which time the glacier may move as much as 50 metres a day or even more for a period of a year or so. Some surging glaciers have advanced several kilometres in as many months.

The basic cause of a glacier surge is a build-up of stress and meltwater within the glacier with which the glacier's natural drainage system cannot cope. Water is blocked underneath the upper part of the glacier, and a bulging, heavily-fissured surge front begins to migrate down the glacier. If this front reaches the edge of the glacier, it may advance several kilometres very rapidly, sometimes blocking up valley rivers. The rumblings and vibrations of a surging glacier can often be heard several kilometres away. The surge normally ends when a

A sudden glacier flood that carried mud and debris through the Swiss village of Münster in 1987.

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sudden flood releases the pressurized water blocked under the upper part of the glacier.

The characteristics of calving instability are the exact opposite: the slow advance and catastrophic retreat of glaciers that end in the deep water of lakes and fjords. What triggers the onset of calving instability is not clear but the effects can be dramatic. Parts of the glacier snout, which normally rest on a moraine—the accumulation of debris brought down by the glacier—in shallow water, break off as a result of melting by warm water. As the glacier retreats, it encounters deeper water and calving accelerates rapidly as more and more of the glacier comes into contact with water warm enough to melt it. This continues until the glacier has retreated so far that its snout rests once again in shallow water.

The largest glacier retreat ever observed was probably the 100-km recession of ice in Alaska's Glacier Bay. Fortunately, glaciology is now sufficiently advanced to be able to predict, in some cases, the onset of calving instability. Such was the case with the retreat of the Columbia glacier, which spewed icebergs into Prince William Sound and across the paths of tankers travelling to and from the pipeline terminal at Valdez.

Photographs illustrate the main characteristics of glacier movement:

1. *A steady-state glacier, a river of ice flowing like a giant freeway.*
2. *The surge of the Plomo glacier in Argentina in 1985, which caused the temporary damming of a river.*
3. *The Columbia glacier in 1978 before the onset of the calving instability that triggered the expected 40-km retreat.*

Taking stock

Monitoring the world's glaciers

The coordinated collection of information about glaciers was begun in 1894, in the hope of clarifying the relationship between glaciers and climate, and improving understanding of the Ice Ages. Until about 1950, most of the information collected related to glacier lengths, particularly in the Alps, Scandinavia and Iceland, and many of the observations were made in connection with hazards such as ice avalanches and outbursts from ice-dammed lakes.

Direct mass balance measurements began to be taken after World War II, first in Scandinavia and then elsewhere, many in conjunction with hydroelectric schemes. It was this work that really established the link between climate change and glacier fluctuations.

The need for a worldwide inventory of perennial snow and ice masses was first considered during the International Hydrological Decade operated by UNESCO during 1965–74. The International Commission on Snow and Ice (ICSI, of the International Association of Scientific Hydrology) was asked to prepare guidelines on compiling glacier inventory data, and these were produced in 1970.

Several countries then started to compile glacier data and in 1976 a Temporary Technical Secretariat was established in the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. It soon became clear that the data compiled would not only provide an instantaneous snapshot of the planet's frozen water resources but that they could also serve as the basis for the long-term monitoring of glaciers and would be useful in the study of long-term climatic change. Accordingly,

Many of the first mass balance measurements were made as part of the design and operation of hydropower schemes (left, in photo below) fed by glaciers.

W. Haeberli

when the Global Environment Monitoring System (GEMS) was established, it was agreed that the World Glacier Inventory could be included in GEMS. In 1986 a new service, the World Glacier Monitoring Service, was set up in Zurich as part of GEMS, with financial help from several bodies, mainly UNEP, ETH and the International Council of Scientific Unions.

The original inventory was published in 1989, and reflected the state of glaciological data in the previous year (*World Glacier Inventory: status 1988*, IAHS (ICSI), UNEP, UNESCO, 1989). Its aim was firstly to provide a snapshot of ice conditions on Earth during the second half of the 20th century. Glacier inventories were made worldwide, and then compiled to provide a statistical basis for the study of glaciers. As Figure 10 shows, all the relevant glacierized areas of the world are now covered by some kind of inventory, most of them detailed but a few still preliminary. It is planned to fill the remaining gaps in the near future.

The work of the World Glacier Monitoring Service continues. Its aims are to collect and publish data on glacier fluctuations every five years, and to complete and upgrade the original inventory. In addition, mass balance data are being published every two years because of glaciers' role as key indicators within climate monitoring.

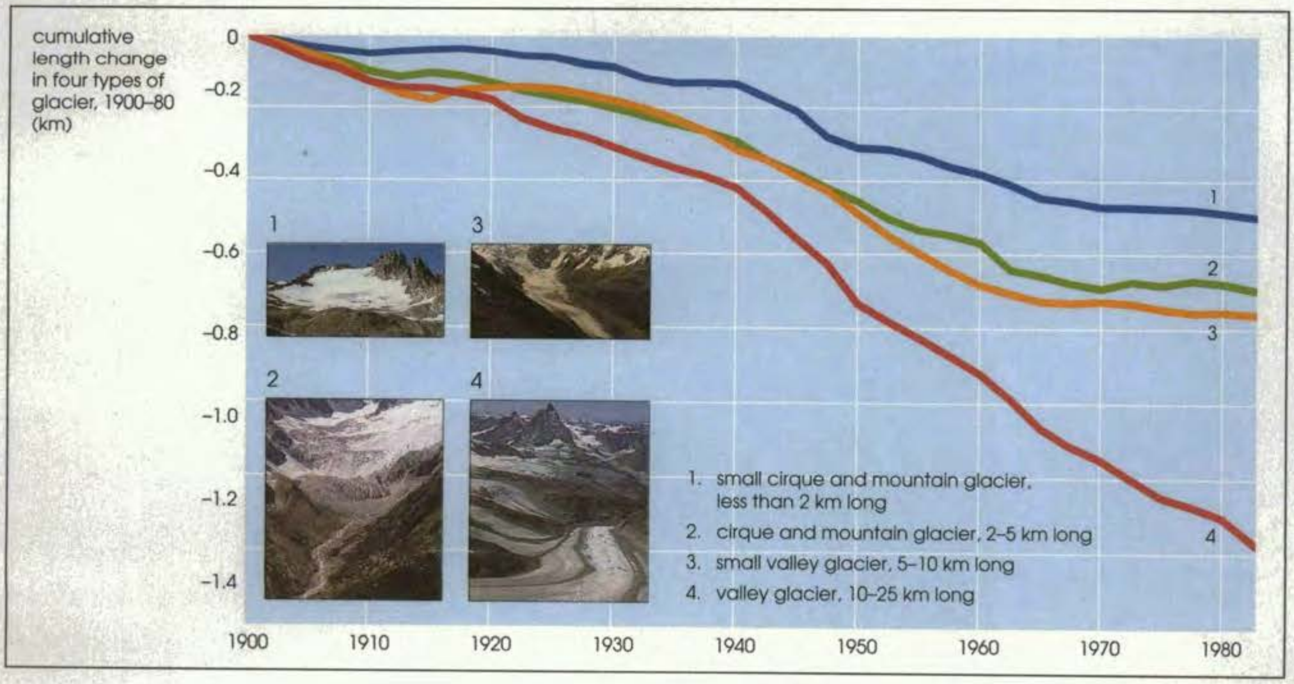
Figure 10 Status of the World Glacier Inventory in 1988. Monitoring is being continued by the World Glacier Monitoring Service in Zurich. Antarctica is not included since, although it contains some 30 million km^3 of ice, no formal attempt has yet been made to compile a glacier inventory for mainland Antartica.

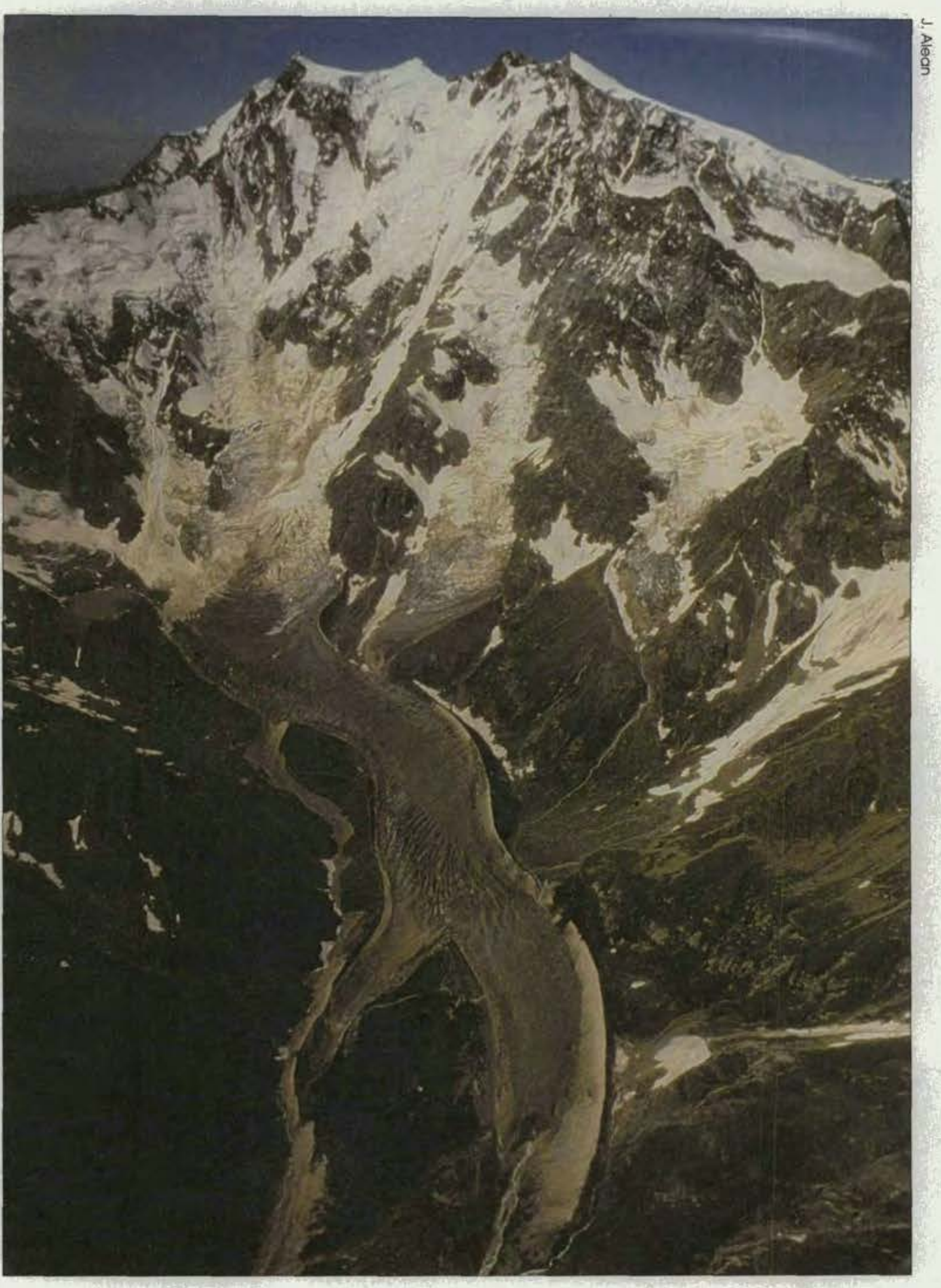
Uses of the data

The inventory data are already proving useful in a number of ways. For example, the data showed that most of the ice in regions of North America where there are long valley glaciers is contained in the largest and thickest glaciers; in the Alps, by contrast, most of the ice is to be found in small, thin mountain glaciers. This has implications related to global warming. The North American glaciers are likely to provide glacier meltwater to the sea—one of several causes of sea level rise— for a considerable time before the flow is reduced because the glaciers have become smaller. In the Alps, however, most glaciers will be reduced in size fairly rapidly and many could disappear. About half the ice that existed in the Alps at the end of the Little Ice Age has already melted as a result of 20th-century warming; a further reduction to perhaps one-quarter of today's area and a few percent of today's volume is to be expected if the next century is markedly warmer than this one.

Glacier monitoring now attempts to provide several types of information. Observations on glacier length are the key to comparing today's glaciers with those of the past. The technical difficulties of glacier monitoring mean that remote glaciers must be monitored by aerial photography and high-resolution satellite imagery. At the same time, meaningful comparisons of glacier data can be made only where the data span relatively long periods of times and exist for carefully designed groups of glaciers. A good example is shown in Figure 11. These groups will provide the baseline data from which glaciologists will have to work as they try to interpret what future changes in mass balance tell us of climate change and global warming.

Figure 11 Long time-series data on glacier length are invaluable material for the world-wide analysis of glacier response to climatic changes over long time scales. Note how much more valley glaciers respond to climate change than do small mountain glaciers.





J. Alean

The Belvedere glacier in Italy, covered with debris and including a moraine-trapped lake. The risk of glacier floods from such lakes is increasing as 20th-century warming causes glaciers to retreat.

More detailed information will be useful on glaciers where physical measurements can be made. Mass balance observations can be correlated with climate change and this has enabled experts to assess the sensitivity of glaciers to climate change in relation to the altitude of their equilibrium lines. Observed changes in glacier mass can also be expressed as energy changes, thus allowing experts to make direct comparisons between changes in glacier mass and anthropogenic enhancement of the greenhouse effect. The overall shrinking tendency of glaciers in the Alps—for which the best documentation exists—is broadly consistent with the estimated anthropogenic greenhouse warming and now seems to be leading, increasingly quickly, to climatic conditions outside the range of the climatic variations that have occurred since the end of the past Ice Age.

One of the original aims of the inventory was to evaluate the freshwater resources stored in perennial snow and ice on a global scale. This aim proved somewhat ambitious but the inventory data so far compiled have already been of great use in estimating high-altitude precipitation and potential run-off from mountain areas where it is difficult to establish precipitation gauges.

Finally, monitoring is providing a systematic collection of data on special events such as glacier surges, the instability of tidal glaciers, glacier floods, ice avalanches and eruptions of ice-clad volcanoes. The compilation of this material is an important addition to data on natural disasters and may be of future use in elaborating early warning systems to mitigate the effects of glacier-related hazards. The relevance of these data is likely to increase, if only because the formation of lakes on the margins of retreating glaciers as a result of 20th-century warming is continually increasing the hazards from glacier floods.

A century ago, when glacier monitoring began, it was clear that decades of patient work would be needed before the scientific study of glaciers could bear useful fruit. This it has now done—just in time, probably, to help in the battle against the effects of the enhanced greenhouse effect and the global warming that seems likely to follow it. Glacier fluctuations already provide the most important evidence we have of 20th-century warming. The importance of monitoring glaciers will certainly increase if enhanced greenhouse gas warming turns from a prediction to a reality. Glaciology has always been interesting; more recently it also became important. Now its development has become urgent.

Much more remains to be done. There is a need for more and better data, for improved communication between observers, modellers and theorists, and for the more widespread introduction of advanced techniques, particularly high-resolution remote sensing. The World Glacier Inventory is a beginning on a long road—a road that may turn out to be very long indeed.

Sources

Clarke, G. K. C., A Short History of Scientific Investigations on Glaciers, *Journal of Glaciology*, pp 4–24, special issue, 1987.

Denton, G. H. and Hughes, T. J. (eds.), *The Last Great Ice Sheets*, New York, Wiley, 1981.

Field, W. O., *Mountain Glaciers of the Northern Hemisphere*, Hanover, CRREL, 1975.

Haeberli, W., Glacier and permafrost signals of 20th-century warming, *Annals of Glaciology* 14, pp 99–101, 1990.

Haeberli, W., Müller, P., Alean, P. and Bösch, H., Glacier changes following the Little Ice Age—a survey of the international data basis and its perspectives, in J. Oerlemans (ed.), *Glacier Fluctuations and Climatic Change*, pp 77–101, Dordrecht, Kluwer Academic Publishers, 1989.

Imbrie, J. and Palmer, K., *Ice Ages*, Cambridge, Harvard University Press, 1979.

Paterson, W. S. B., *The Physics of Glaciers*, Oxford, Pergamon Press, 1981.

Robin, G. de Q., and Swithinbank, C., Fifty years of progress in understanding ice sheets, *Journal of Glaciology*, pp 33–47, special issue, 1987.

Sugden, D. E. and John, B. S., *Glaciers and Landscape*, London, Edward Arnold, 1976.

Shumskyi, P. A., *Principles of Structural Glaciology*, New York, Dover Publications, 1964.

Technical Reports of the World Glacier Monitoring Service

IAHS, *World Glacier Inventory—Proceedings of the Riederalp Workshop*, IAHS Publication No. 126, 1980.

IAHS (ICSI) and UNESCO, *Fluctuations of Glaciers 1959–1965* (edited by P. Kasser), Paris, 1967.

IAHS (ICSI) and UNESCO, *Fluctuations of Glaciers 1965–1970* (edited by P. Kasser), Paris, 1973.

IAHS (ICSI) and UNESCO, *Fluctuations of Glaciers 1970–1975* (edited by F. Müller), Paris, 1977.

IAHS (ICSI) and UNESCO, *Fluctuations of Glaciers 1975–1980* (edited by W. Haeberli), Paris, 1985.

IAHS (ISCSI)/UNEP/UNESCO, *Fluctuations of Glaciers 1980–1985* (edited by W. Haeberli and P. Müller), Paris, 1988.

IAHS (ISCSI)/UNEP/UNESCO, *Fluctuations of Glaciers 1985–1990* (edited by W. Haeberli and M. Hoelzle), to be published in 1993.

IAHS (ICSI)/UNEP/UNESCO, *Glacier Mass Balance Bulletin No. 1*, 1988–1989, WGMS/ETH, Zurich, 1991.

IAHS (ICSI)/UNEP/UNESCO, *Glacier Mass Balance Bulletin No. 2*, 1990–1981, WGMS/ETH, Zurich, 1992.

IAHS (ICSI)/UNEP/UNESCO, *World Glacier Inventory: status 1988* (edited by W. Haeberli, H. Bösch, K. Scherler, G. Østrem and C. C. Wallén), Nairobi, 1989.

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