Ice on the move

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Glaciology, from the Latin word for ice, is a much wider subject than most people think. Studying glaciers is only one of its branches, for it embraces the investigation of ice in all its forms. Ice occurs naturally in many different forms and sizes, from polar ice-sheets, Alpine valley glaciers, permafrost (where ground is frozen throughout the year), sea-ice and annual snow patches, to hailstones and snow-fall. We grow ice in the laboratory to study its physical properties and to help find out how it behaves in nature, how ice in large masses flows, how ice crystals are seeded in the atmosphere to form hail and snow, how the destructive effects of avalanches may be reduced, how skis can be made to go faster and how to solve a great many other problems, both economic and scientific.

Not surprisingly it is those countries with a lot of ice that show the most interest in glaciology. One exception is Britain. Although this country has no perennial snow, it has produced, in men like Tyndall and Forbes who ranged the European Alps more than 100 years ago, some of the founders of the science, and has nurtured men and institutions now at its forefront.

More and more glacial research is being done because people throughout the world are becoming aware of how important ice is to them. The huge reservoirs of ice in Greenland and Antarctica control world sea levels. They greatly influence global atmospheric circulation and, through it, the weather and the climate. We can monitor global pollution by analysing Antarctic snows, gathered in an otherwise uncontaminated environment. To exploit mineral resources in polar regions we need to understand the natural conditions there, the variability and extent of sea-ice and icebergs, the properties of tundra and permafrost across which giant oil pipes may pass, the bearing capacity of pack-ice, and how ice and snow accrete on and around buildings and structures. Hydrologists need to know how much snow and ice there is each year and how it varies from year to year, to help in estimating water run-off for the generation of hydro-electricity, irrigation, flood control and navigation on inland waterways.

Studies of the flow of ice in glaciers and ice-sheets lead to an understanding of the flow of crystalline materials in general. The models they provide may give us an insight into how rocks in the Earth's crust and mantle deform over periods of millions of years. Interest in climatic change is reflected in the study of samples bored from ice-sheets which contain an unbroken sequence of snow deposits in chronological order with depth. One topical question always being asked is when the next ice-age will arrive; so far no-one can give an answer.

Ice distribution

Nearly 99 per cent of the available fresh water in the world is in the form of ice, comprising a total volume of 30 million cubic kilometres. The Antarctic and Greenland ice-sheets together hold 99 per cent of the ice, smaller glaciers and snow-fields contain one per cent, and all the rivers, lakes and moisture in the soil and atmosphere together make up the remaining one per cent of fresh

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23 Nisqually glacier on Mount Rainier (This and next two photos: International Glaciological Society)

water. More than a tenth of the land surface (3 per cent of the total surface of the Earth) is covered by ice; during the recent ice-ages the area covered was almost 3 times as large.

One-quarter of the land is covered by snow for more than 4 months each year. During an average year, snow for some time covers half the land surface and, for short periods only, as much as 85 per cent. Sea-ice has a large annual

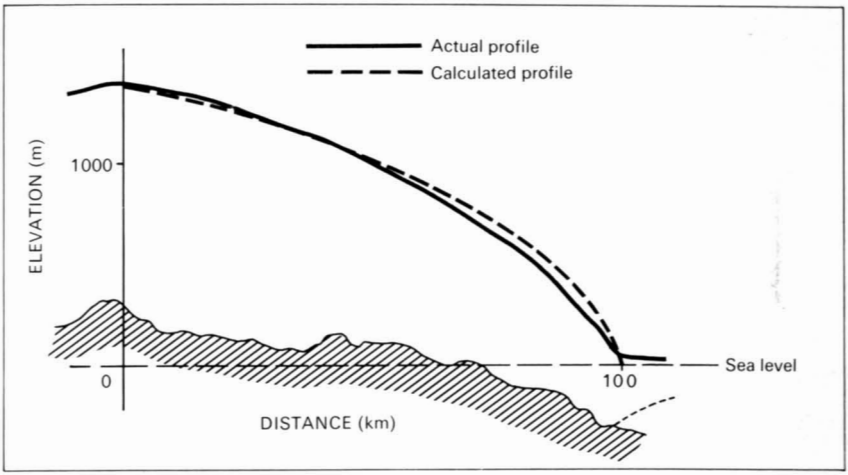


Fig 1 Surface profile of an ice-cap or inland ice-sheet. It is nearly parabolic and is uninfluenced by the topography of the bed rock

and seasonal variation, with an average maximum coverage of 6 per cent of the world. Snow and hail falls are estimated to account for 5 per cent of the total annual precipitation.

Glaciers are formed by the accumulation of snow. As the snow becomes more dense through compaction by the weight of additional snow-falls it turns gradually into ice, at a rate depending on temperature. Glacier ice forms more quickly in temperate regions; there, summer melting may allow more water to percolate through snow than in polar regions, where the snow may stay frozen throughout the year. In Greenland and Antarctica ice has built up to cover the land with vast ice-sheets. Because of its ice, the surface of Antarctica is the highest of all the continents. Its coastline is fringed by floating ice-shelves up to 1300m thick.

In contrast to the land-based ice-sheets, the deep Arctic Ocean has a thin covering of sea-ice. Pack-ice consists of a large number of floes with an average thickness of only a few metres, though pressure ridges, formed by ice moving under the action of wind and sea currents, may be 30 or 40m thick. Even in mid-winter the continual motion of the floes ensures that there is always some open water; to be able to detect this, as well as to know the topography of the deep pressure ridges, is important to submarines under the ice.

Mountain glaciers are found in many parts of the world, even straddling the equator in countries like Peru and Kenya. Ice-caps, somewhere in size between ice-sheets and valley glaciers, occur in Arctic Canada, Iceland, Scandinavia and Patagonia. There is an almost infinite gradation of glacier types between a cirque glacier, which produces an 'arm-chair' shape, and a polar ice-sheet.

It is useful to distinguish between glaciers whose ice is at the melting point and those whose ice is below the freezing point. The former are known as temperate and the latter as polar glaciers; the terms refer to the ice temperature and not to their latitude. Because conditions may vary from place to place on a glacier, few of them can be classified into a single category. It is often better to describe different zones on a glacier, such as the dry accumulation zone



24 Avalanche in Switzerland

where no melting takes place, the percolation, soaked and superimposed ice zones, which have an increasing amount of surface melting, and finally the ablation zone, where the surface is carried away by water.

Fresh-water source

The importance to many countries of ice and snow as fresh-water resources led to a world-wide study of selected glacier systems during the International Hydrological Decade (1964-74). During that period 3 chains of glacier basins around the world were studied for their balances in the exchange of water, ice, and heat. From this we hope that the relationship between the mass of a glacier, reflected in its size and length, and its climatic environment will be worked out. It may then be possible to understand how glaciers can act as indicators of climatic change.

Theoretical advances have been made in this over the last 10 years or so, based on the phenomenon of kinematic waves which occur in flow systems such as road traffic and flooding rivers, and which propagate the effects of mass balance changes down the glacier. Although it may be possible to deduce recent climatic change from observations of glacier fluctuations, it looks as if the reverse problem of predicting how a glacier will respond to a change in climate requires meteorological data for hundreds of years. This is unfortunate, because forecasting glacier fluctuations is a problem which concerns Switzerland and other countries where dams and power stations have been built in places that could be threatened by a big glacial advance.

In countries like Norway, which produce most of their electric power by hydroelectric plants, often using water run-off from glacier basins, it is necessary to consider the annual variation in water discharge from melting snow. The way the snow-line varies throughout the year can be detected by satellites and is being investigated in several regions. Variations in the snow cover, calculated from satellite pictures, will help in predicting the amount of water that will run off. The information is also needed in agriculture and for flood control as well as to help in forecasting avalanches.

A novel source of fresh water in the future may be icebergs. It may be as cheap to tow large tabular bergs from Antarctica to coastal sites in Australia, Africa and even North America, as it is to provide water supplies by other means. The biggest problems appear to be in processing the iceberg. Its draft would probably be about 200m, greater than the depth of water above most continental shelves. But favourable deep-water sites do exist and, in spite of the sea cooling near moored icebergs and the possibility of changes in the local climate, the benefits of being able to irrigate very large areas of otherwise arid land could make the effort worth-while. Many other difficulties need to be overcome before towing icebergs on a large scale becomes feasible.

Nevertheless, towing of small icebergs is an established technique off the coast of Labrador, in Canada. There, Greenland glaciers breaking out into the sea form icebergs which drift through an area where there are many oil rigs. Ships stand by ready to net any iceberg that heads towards a rig, to deflect it away.

25 Terminus of the Gilkey glacier, Alaska



Ice flow

Early travellers in the Alps compared glaciers to rivers of ice. The implication that ice behaved as a Newtonian fluid with a very high constant viscosity proved a hindrance to the development of theories of glacier flow. A big advance around 1948 was the realization that the flow law for ice should be similar to that for other polycrystalline materials, namely metals, near their melting points. The flow law describes the relationship between stress and strain rate, and the proper formulation of this law is fundamental to understanding the motion of ice in glaciers and ice-sheets. Much laboratory work has been carried out both on single crystals and polycrystalline samples under various conditions of stress. The results are complemented by others from field studies covering a range of low stresses and long periods over which stresses are applied in nature, which cannot be reproduced in the laboratory. All this has given us a much better understanding of glacier movement but the problem of what governs the flow has not been completely solved. For example, there is still uncertainty about the effect of crystal orientation, which is not usually allowed for in the flow law. The predicted surface profile of ice-sheets and ice-caps using the accepted flow law corresponds closely to those of Greenland and Antarctica but it is difficult to obtain analytical solutions for general problems. This is because the flow law is both temperature-dependent and non-linear (the strain rate increases sharply as the load increases).

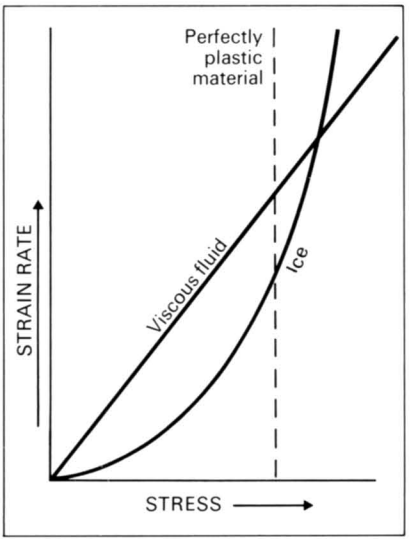


Fig 2 Non-linear behaviour of the flow law for ice. Because of this characteristic it is, for some purposes, a good approximation to regard ice as a perfectly plastic material

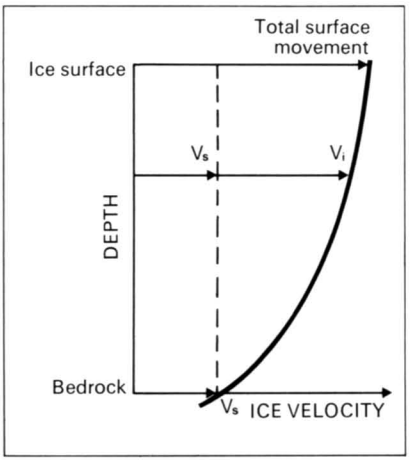


Fig 3 Velocity profile of a glacier. V_s is the velocity component due to ice sliding over its bed and V_i the velocity component due to internal deformation of the ice. The velocity of the ice at any particular depth is $V_s + V_i$

Velocity profile

Glacier flow can be considered to consist of 2 components; one is the sliding of the base of the glacier over its bed, and the other is caused by deformation of ice in the body of the glacier. This is shown in what is known as the velocity profile. Basal sliding occurs only when the temperature of the ice at the bottom of the glacier is at its pressure melting point, and may account for up to 80 per cent or more of the total surface movement in some glaciers.

At its extreme, glacier sliding may cause the phenomenon of surging. Some glaciers, apparently periodically, greatly increase their velocity and may move at speeds of several kilometres a year. Usually, they relapse after a short time into their former quiescent state, with a general lowering of the surface in the upper region to compensate for a transfer of ice to lower regions, so increasing the total length. The mechanism leading to this surging appears to depend on water lubricating the base of the glacier, but the details are still not properly understood. The component of velocity caused by internal deformation depends on the distribution of stress in the ice; the flow law can be used either to calculate the velocity profile or to interpret data about the velocity obtained from boreholes.

Radio echo sounding

One big British contribution to the study of ice masses is the development of radio echo sounding, a technique similar to radar. A pulse of electromagnetic waves is sent through the ice and the echo reflected from the bedrock is detected. The velocity of radio waves in ice is known, so the echo delay represents the thickness of the ice. Advantages of this method are that it yields a continuous profile of the bedrock, in contrast to spot readings obtained from seismic and gravity soundings, and the equipment may be operated from aircraft to survey large and otherwise inaccessible areas. The thickness of the ice over much of Antarctica has now been mapped by the Scott Polar Research Institute and the British Antarctic Survey.

By making use of the way the attenuation of radio waves in ice varies with temperature, it has been possible broadly to confirm theoretical predictions of the temperatures in large ice masses. Other results from Antarctica have revealed mountain ranges completely submerged by ice and the presence of lakes of water under more than 3km of ice. This last discovery prompted a re-examination of proposals to dispose of the world's radioactive wastes in Antarctica. Heat produced by radioactive decay would enable containers to melt their way down through the ice to bedrock, in areas where ice movement is slow enough to keep the toxic wastes isolated until they become harmless after a few hundred thousand years. But the circulation of water at the base of the ice could release wastes into the ocean while they are still toxic. In spite of the urgency of the problem, the possibility of leakage of contaminated water and the irretrievability of the containers makes the proposals unacceptable.