# GLACIERS

**A C Fowler**, University of Oxford, Oxford, UK



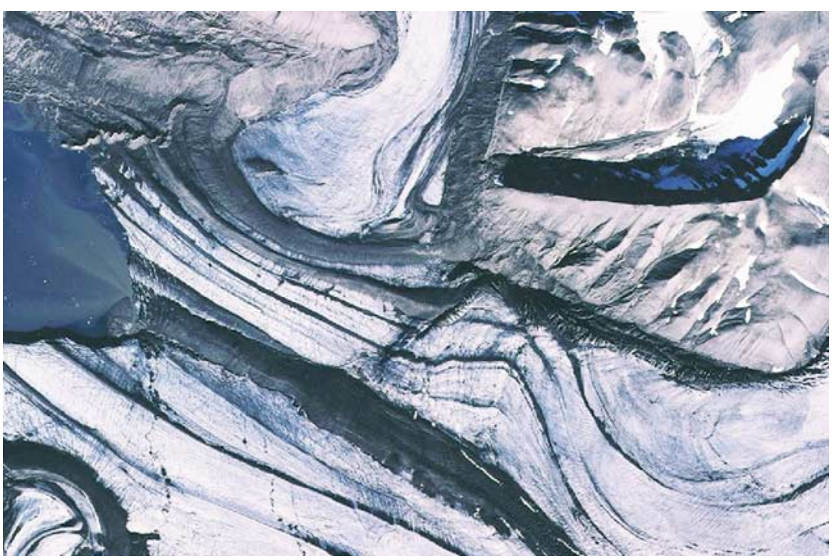
## Introduction

0158-P0005 Glaciers are rivers of ice, and ice sheets are continental-scale domes of ice. Both glaciers and ice sheets flow slowly, transporting snow which falls at high elevation (and is compacted to form ice) to lower elevations, where it melts or is released into the sea as icebergs. The size and extent of glaciers varies with climate, and they represent the most slowly responding constituent of the global climate system of oceans, atmosphere and cryosphere. Despite this, glaciers and ice sheets are capable of surprising and dramatic effects such as glacier surges, and are thought to have been an important causative component of the rapid climate shifts seen in the last ice age.

0158-P0010 Glaciers are found either in regions of high elevation, such as in the Alps or the Himalayas, or in polar regions, such as Alaska or Svalbard (**Figure 1**). Typical depths are on the order of hundreds of meters, and typical lengths are measured in kilometers; the Bering Glacier in Alaska is one of the longest, at 200 km. Glaciers form when snow accumulates to great depth, and is transformed through the effects of pressure to form ice, which then creeps slowly down slope, at rates which are typically measured in tens to hundreds of meters per year. The fastest moving glacier on Earth is the outlet glacier Jakobshavn in Greenland, which moves steadily at a brisk 8 km $y^{-1}$.

Glaciers perform the same functions as do rivers, 0158-P0015
acting both as an agent of water transport, and as an agent of erosion. Glaciers, along with landslides, are the primary agents of erosion in high mountain ranges, and they are also instrumental in forming various landscape features, such as U-shaped valleys, terminal moraines, drumlins, and eskers. Glacial climate is also associated with the formation of permafrost-related features, for example fossil ice-wedge polygons; the former presence of glaciers and ice sheets in North America and Northern Europe during a sequence of ice ages (the last of which terminated some 10 000 years ago) is demonstrated by the presence of these and other such signatures as erratics (isolated boulders transported by the ice), and glacial striae and scratches in bedrock, which can, for example, be found in Central Park in New York.

In sufficiently cold conditions, a network of glaciers 0158-P0020
will coalesce and grow to form an ice cap, or, at the largest scale, an ice sheet. There are two present-day ice sheets on the Earth – those which cover most of Greenland and Antarctica – and their dimensions are measured in thousands of kilometers (horizontally) and thousands of meters depth. During the ice ages, however, other ice sheets grew to cover much of North America, Scandinavia and Britain, and their former presence is betrayed by such relict features as moraines



0158-F0001 **Figure 1** A vertical view of Bakaninbreen Glacier in Svalbard, 1990. Flow is from bottom right towards the top left. The dark lines in the ice are medial moraines. Bakaninbreen is a surging glacier, and the advancing surge front is clearly visible in the centre of the picture (Photo courtesy Tavi Murray.)

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(e.g., Cape Cod), drumlin fields (e.g., across the north of Ireland), and glacially excavated fjords and lochs.

0158-P0025 Most glacial ice is found in these large ice sheets; the remainder exists in glaciers and ice caps which occur in mountainous regions, largely round the Arctic Ocean basin in the Northern Hemisphere. Extensive systems of glaciers exist in the Andes, Alaska, Norway, the European Alps, and the Himalayas. Glaciers are also found in warmer regions at sufficently high altitude, for example, in equatorial parts of Indonesia and Africa; such glaciers are known as tropical glaciers.

0158-P0030 Glacial extent is thus an indicator of climate (with a 10 to 100 year response time), and the recession of many glaciers during the twentieth century marked a noticeable global warming which terminated a centuries-long cold period, known as the Little Ice Age, which lasted from about AD 1500 to 1900. The change in climate in Europe over the last hundred years is evidenced by the shrinking glaciers in the Alps, and more poetically by the plentifulness of snow in Impressionist paintings of the late nineteenth century.

0158-P0035 Glaciers respond to climate in a similar way to rivers, by the passage of kinematic waves (somewhat like flood waves on rivers) down the glacier, with a characteristic speed of transmission of several times the surface speed. Ice sheets also respond to climatic change, but on a much longer time scale, of the order of tens of millennia. It seems likely that the time scale of the regular occurrence of ice ages over the last several million years, with a slow growth of the ice sheets over a period of some 90 000 years, followed by a relatively abrupt decline over some 10 000 years, is associated with this response time of the large ice sheets, and their effect on climate through the effect of ice–albedo feedback.

0158-P0040 Glaciers exhibit a variety of other wavelike motions, which appear to be internally generated and unrelated to climate. Wave ogives and 'Schnellungswellen', or waves of velocity, are seasonal effects. More dramatic is the glacier surge (**Figure 2**), a rapid advance of a glacier that occurs for a short time, and is repeated at regular intervals. A well-documented example of a surging glacier is the Variegated Glacier in Alaska, which surges rapidly for one to two years, repeating this behaviour at intervals of about 20 years. Velocities during surges can increase by a factor of a hundred, and advances of 10 km or more in less than a year have been recorded.

0158-P0045 Modern-day ice sheets do not, on the face of it, appear to exhibit such collective surge-type behavior, but they do exhibit a spatial equivalent to the temporal periodicity of surging valley glaciers, in the existence of concentrated 'ice streams' (**Figure 3**). A well-known example occurs on the Siple Coast in Antarctica, where the ice which drains into the floating Ross ice shelf is segregated into five separate ice streams, four of which move much more rapidly than the bounding, relatively quiescent ice. The Whillans ice stream, for example, moves at speeds of 500 m $y^{-1}$, as opposed to neighboring ice speeds of less than 10 m $y^{-1}$. The ice streams are recognizable from the air by their intensely crevassed surface, a feature they share with surging glaciers during the active surge phase. In the Siple Coast, they have typical widths of 40 km, and lengths

0158-F0002 **Figure 2** A closer view of the surging Bakaninbreen Glacier, 1987. The ice attains depths of 300 m, and is 1–2 km wide. The ridge in the picture is the surge front, a wall of ice some 50 m high, propagating down glacier at about a kilometre per year. (Photo courtesy Tavi Murray.)

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0158-F0003 **Figure 3** Aerial view of the Stancomb Wills ice stream flowing into the Brunt ice shelf, Antarctica. The highly crevassed nature of the surface is typical of a fast-flowing ice stream. (Photo courtesy British Antarctic Survey.)

of several hundreds of kilometers. There is also evidence of ice streams in former Northern Hemisphere ice sheets, for example the Laurentide ice sheet in North America was drained by a number of ice streams, amongst them one, some 200 km wide, which flowed out into the Labrador Sea down the Hudson Strait.

## Physics of Glaciers

0158-P0050 Ice is a crystalline solid, and behaves over short time scales, like other rocks, as an elastic medium when subjected to differential stresses; in particular, it fractures in tension, and these fractures are manifested on glaciers as the crevasses which are commonly seen at the glacier surface. Over a longer time scale, however, ice will deform like a viscous fluid due to the stress-induced migration of dislocations within the crystalline lattice structure. Such dislocation creep can be measured experimentally, and the effective viscosity is found to depend nonlinearly both on the applied stress and the temperature: higher stresses and temperature both act to make the ice less 'sticky'. At a typical glacier stress of one bar (0.1 MPa) and a temperature near the melting point (273 K), the viscosity is about $10^{13}$ Pa s, or in more prosaic units, about 4 bar year. The shear modulus for elastic deformation of ice is about $3.5 \times 10^9$ Pa, and the ratio of these, some 3000 s, or 50 min, defines the Maxwell time which separates short term elastic behavior from long term viscous behavior. For time scales greater than a few hours, ice behaves viscously, at least at such high temperatures. For colder ice at lower stress, the Maxwell time may be of the order of months, or longer.

Mathematical models of the flow of glaciers and ice 0158-P0055 sheets take advantage of the fact that they have a high aspect ratio, like the atmosphere, so that a form of lubrication, or thin film, approximation is appropriate. In the simplest version of such models, which assume a temperature and moisture-independent flow law, one derives a convective diffusion equation for the glacier depth, or a nonlinear diffusion equation for the ice sheet depth. Unfortunately, such models are unrealistic, because of the strong effect of temperature on the flow law (for glaciers at sub-freezing temperature), or because of the effect of moisture on the flow law (for temperate glaciers, at the melting point).

Ice is an insulator, and because of this and the 0158-P0060 warming effects of geothermally derived heat, as well as heat generated by stress working in the ice, the temperature, as well as the stress, increases with depth, particularly near the base where the effects of advection are generally smaller. At a temperature of $-20°$C, the viscosity is 40 times greater than at the melting point, and at $-50°$C, as is appropriate to parts of the the Antarctic ice sheet surface, it is 2000 times greater. A reduction of stress by a factor of 10 near the surface would cause a further increase by a factor of 100. Thus ice is in fact a strongly variable viscosity medium, and its motion is more akin to that of a fairly rigid layer being carried along on top of a softer shearing underbelly. Because of this, one needs to solve the energy equation for the temperature also.

A novelty in ice physics is that the frictional heating 0158-P0065 due to viscous dissipation is important. Because the heating depends nonlinearly on temperature, the

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temperature and flow equations are coupled via a positive feedback (faster flow means more heat, hence higher temperatures, hence reduced viscosity, hence higher velocity), and the possibility arises of thermal runaway occurring (the same phenomenon is the cause of explosions, and also of the combustion that occurs in lighting a match). It has been suggested that such an instability lies at the root of surging glacier behavior, and also of ice streaming, but it is unlikely that this can be the whole story.

0158-P0070 The reason for this is that the rise in temperature near the base of a glacier has another important effect. If the temperature reaches the melting point (and this is often the case), then basal melting starts to occur, and water will exist at the glacier bed. In this situation basal ice motion, or sliding, occurs, and this is thought to be the cause of much of the fast flow exhibited by ice streams and surging glaciers. The basal water forms its own subglacial drainage system, and flows towards the glacier outlet. It is a common experience to see one or more outlet streams emerging from the front of a glacier, often from a large portal. In addition, surface rainwater or meltwater often finds its way to the bed via crevasses or moulins. It is common to see streams on a glacier surface which suddenly disappear down a hole, presumably to connect to the basal water system.

## Thermal Classification

0158-P0075 The presence and amount of water in a glacier is associated with a thermal classification of glaciers. The basic types suggested by Ahlmann in 1935 are the polar and temperate glaciers. As its name suggests, the polar glacier is one which is below the melting temperature throughout, and occurs (if at all) in polar regions. At the other extreme, a temperate glacier is at the melting point throughout, and contains a small amount of liquid water in inclusions. Most glaciers in the Alps are temperate, and contain typically 2% by volume of water.

The mechanism by which a glacier can be temperate 0158-P0080
is ascribed to the seasonal variation in temperature. In temperate climates, snowfall on a glacier during winter is melted in the summer, and the resulting meltwater percolates through the porous upper snow (or firn, i.e., wet snow) where it refreezes, and the resulting release of latent heat enables the temperature to be maintained at the melting point. Various further classifications can be made in order to allow for the common situation where a glacier in a polar environment has a surficial cold layer, but the basal ice is warmed by geothermal heat to the melting point (**Figure 4**); sometimes a basal temperate layer may form, where the ice is internally heated to melting point and may contain water inclusions. Glaciers of this and similar type are often called 'sub-polar'; another common term in current usage is 'polythermal'.

## Basal Sliding

The effect of basal water on the motion of ice is that it 0158-P0085
allows basal slip, or basal sliding, to occur. The mechanism whereby this is thought to occur is a subtle one. When the basal ice is at the melting point, a thin (micrometer thick) water layer exists between the ice and the underlying bedrock, due to regelation: the ice approaching the upstream (stoss) face of a protruding

0158-F0004 **Figure 4** Trapridge Glacier, a surge-type sub-polar glacier in the Yukon Territory, Canada. The glacier is 4 km long and the advancing front is about 70 m high. (Photo courtesy Garry Clarke.)

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bump is at higher pressure, and thus melts, because the melting temperature decreases slightly with increasing pressure (the Clapeyron effect); this meltwater forms the thin film, which then squirts round the bump under the driving pressure gradient, to refreeze downstream where the pressure is lower. The latent heat necessary is provided by conductive heat transfer through the rock.

0158-P0090 Regelation itself allows a mechanism for flow of ice, but also the film lubricates the ice–bed interface, so that the ice can simply flow viscously over the bumpy bed. The bed does offer a resistance because of its roughness, and the resulting basal shear stress is related to the sliding velocity by the sliding law. Various theories have been proposed for this ‘law’; in general, as one would expect, the stress increases with the velocity. Sliding at the bed has been observed, and indeed it is the dominant cause of motion in some glaciers.

0158-P0095 Another observed feature of the process of sliding is the formation of cavities. As with ordinary hydraulic cavities, these will form if the water film pressure becomes less than the local subglacial drainage pressure (which is determined independently). Cavities will occur if the sliding velocity is high enough, and they reduce the resistance of the bed; thus the sliding law should also depend on the degree of cavitation, and this will depend on the local drainage pressure. In this way the flow of the ice becomes coupled through the basal sliding law to the subglacial hydraulic system.

0158-P0100 Although the discussion above refers to a clean interface between ice and bedrock, it is usually the case that a certain amount of erosional debris is situated at the bed, often consisting of a mixture of coarse, angular rock fragments within a finer grained matrix of sandy or clayey material. The resultant material is called till, and when water saturated, it will deform. A different kind of basal motion can then occur, wherein ice slides over underlying bedrock via the lubricating effect of the deforming till. This also will lead to an effective sliding law, in which basal shear stress depends on basal velocity and, again on basal water pressure, since the flow resistance of till also depends on this. Meters thick layers of till underlie many glaciers, as well as the Siple Coast ice streams, and it is thought that it is largely the motion of ice over such till layers at high water pressure which causes the fast flow seen in ice streams, and in some surging glaciers.

## Subglacial Hydrology

0158-P0105 In many cases, basal water storage has a profound effect on the dynamics of glaciers and ice sheets, and it is important to understand and quantify the way in which subglacial drainage systems work. There are several different topologies that have been suggested. The principal one is embodied in the concept of the Röthlisberger channel, which is a cylindrical drainage channel at the bed, cut upwards into the ice. The water flows through the channel at a lower pressure than the overburden ice pressure (the difference between the two is called the effective pressure), and consequently the channel (like a void in a fluid) tends to close because of inward creep of the ice. It is maintained open because the water flow through the channel generates sufficient frictional heat to melt the channel walls back. A theory to describe this dynamic interaction leads to a prediction for the effective pressure as a weakly increasing function of the water flux through the channel, and observed borehole water pressures of tens of bars below flotation levels can easily be explained in this way. The fact that effective pressure increases with water flux implies some kind of arterial drainage system, since a larger channel with larger flow rate has a lower pressure than a smaller channel, and hence will suck water from it; thus it is unlikely that Röthlisberger channels are uniformly distributed across the bed.

On the other hand, there is evidence from borehole 0158-P0110
discharge events that in some circumstances (and particularly during a glacier surge) the drainage system may indeed become distributed in some kind of anastomosing pattern. One such system occurs if the channel system closes down, and the water migrates to the cavities. This forms a ‘linked-cavity’ system, and was inferred to occur during the 1982–83 surge of Variegated Glacier. Another type of distributed system that has been suggested is a system of anastomosing ‘canals’, or a system of connected ‘puddles’. Such distributed systems can support much higher water pressure than a Rothlisberger system, and are consistent in this respect with borehole measurements of water pressures near flotation under ice streams.

## Mass and Energy Balance

Glaciers interact with the atmosphere and the oceans 0158-P0115
through processes of mass and energy exchange. Precipitation occurs as snow in winter and accumulates (in the accumulation zone, upstream). Above a certain elevation (the firn line, or equilibrium line), this snow will remain from year to year, and successive snowfalls lead to an increasing thickening and thus compaction of the snow under its own weight, as the air is expelled. In addition, summer melting (where it occurs) allows percolation of meltwater downwards,

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where it refreezes, and both processes lead to the formation of ice, when only isolated air pockets remain. As the ice flows downhill, it descends past the firn line to the ablation zone, where net summer melting outweighs any net snow accumulation, and consequently wastage of the glacier occurs. The resulting melt runs off the glacier, through surface streams or via the basal drainage system, or is evaporated at the surface. Depending on climatic conditions, a glacier may flow all the way to the sea, when it is known as a tidewater glacier. Such glaciers lose mass also by the calving of icebergs (**Figure 5**). The net gain of ice (measured as water equivalent) over a year is known as the mass balance.

0158-P0120 Energy interchange at the glacier surface determines surface temperature (as well as surface melting) in the same way as elsewhere on the Earth's surface, via the balance of incoming short-wave and long-wave radiation with outgoing heat loss by long-wave emission, and sensible and latent heat fluxes. Essentially, the ice will take the mean annual air temperature, at least at depths greater than about 10 m where the surface thermal wave does not penetrate. While this statement would be exact if heat conduction were the only transfer mechanism, it fails when the air temperature becomes greater than the melting point. This is because the ice temperature cannot then follow the air temperature, and the resulting melting and refreezing of melt water at depth causes a much more rapid elimination of the winter cold wave than conduction alone would provide. For these reasons, ice temperature at the glacier surface is only approximately equal to the local mean air temperature.

0158-P0125 Furthermore, surface ablation, while also related to surface air temperature, is not a simple function of it, and is certainly not dependent on mean annual air temperature. It is more directly connected to the mean annual value of the 'positive air temperature', i.e., the air temperature taken only when it is above the melting point. For a glacier or ice sheet, an equilibrium is obtained when net accumulation balances net ablation, thus glaciers act as a climatic indicator of winter precipitation and summer insolation. The latter explains why the summer insolation curves are used in Milankovitch's ice age theory.

## Climatology

Glaciers (and ice sheets) monitor climate, but climate 0158-P0130
also responds to changes in glaciation. A simple example is that of the thermally induced katabatic wind. Obviously, the growth of large ice sheets can potentially exert a thermal and topographic effect on the general circulation, and thus affect precipitation patterns through the diversion of storm tracks. The other, and more fundamental, effect is through the alteration of land surface albedo. Ice and, particularly, fresh snow have a high reflectivity, so that net received surface energy decreases with increasing ice cover. This leads to a positive feedback, called the ice–albedo feedback, which can be used to explain the occurrence of ice ages in simple ('zero-dimensional') models of the climate. In its most basic form, such a model allows two possible stable, steady states; an ice-free Earth (low reflectivity, high received insolation, high global surface temperature), and an ice-covered Earth (high reflectivity, low received insolation, low global surface temperature). Variations of solar insolation due to Milankovitch orbital variations then allow a shuttling backwards and forwards between the two. Although

0158-F0005 **Figure 5** Aerial view of icebergs forming at the edge of the ice shelf near Halley, Antarctica. (Photo courtesy British Antarctic Survey.)

an ice-covered Earth is not attained in the current sequence of ice ages, there is evidence that such a state was reached during a glacial epoch some 600 million years ago; this is the so-called 'snowball Earth' theory.

0158-P0135 Ice sheets are also fundamentally involved in shorter (millennial) time scale climatic switches. Oxygen isotope records from deep ice cores in the Greenland ice sheet show repeated switching during the last ice age between cold and relatively warm conditions. These oscillations, with an amplitude of at least 5°C, are known as Dansgaard–Oeschger events, and they take the form of gradual (millennial) cooling, followed by abrupt (decadal) warming. It has been suggested that these temperature cycles reflect alterations in the oceanic circulation, which is often thought of as a kind of conveyor belt, with downwelling occurring in the North Atlantic, and upwelling in the Indian and Pacific oceans, and around Antarctica. If the conveyor is switched off, then climate becomes cooler, and if it is abruptly switched on again, climate can become abruptly warmer.

0158-P0140 Dansgaard–Oeschger events are bunched into longer time scale cooling cycles lasting about 10 000 years, and these are terminated by Heinrich events, which are followed by dramatic climatic warming. Heinrich events refer to the occurrence in North Atlantic oceanic sediments of layers of ice-rafted debris (IRD), and are thought to be due to a massive discharge of icebergs from the Laurentide ice sheet, and particularly from the ice stream in Hudson Strait, which drained the Hudson Bay ice dome (since the lithic fragments of the IRD largely come from there).

0158-P0145 In some way, it would seem that the massive discharge of ice into the North Atlantic can switch on the global oceanic thermohaline circulation, and lead to sudden dramatic warming of the atmosphere. The way in which such occasional massive discharges can occur is through periodic surges of the Laurentide Ice Sheet through the Hudson Strait ice stream, and the existence of surging glaciers and ice streams shows that such behavior is possible. Alternatively (or as well), tidewater glaciers are known to undergo similar cycles of slow advance and rapid (via iceberg calving) retreat, and these might be associated with the Dansgaard–Oeschger events. In any event, we see that the dynamics of glaciers and ice sheets are likely to have been fundamental in the past in driving the ice age climate, at all time scales from the Milankovitch tuned 100 000-year ice age cycle, through the 10 000-year Heinrich events and millennial Dansgaard–Oeschger events, to the sudden decadal warmings that terminate them; we are only beginning to recognize and understand such behavior. The implication for the study and prognosis of our present climate is clear.

## See also

**Climate Variability:** North Atlantic and Arctic Oscillation. **Energy Balance Model, Surface**. **Hydrology:** Ground and Surface Water; Modeling and Prediction; Overview. **Ice Ages (Milankovitch Theory)**. **Katabatic Winds**. **Permafrost**. **Sea Ice**.

## Further Reading


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