Why the Greenland and Antarctic Ice Sheets are Not Collapsing

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Global warming alarmists have suggested that the ice sheets of Greenland and Antarctica may collapse, causing disastrous sea level rise. This idea is based on the concept of an ice sheet sliding down an inclined plane on a base lubricated by meltwater, which is itself increasing because of global warming.

In reality the Greenland and Antarctic ice sheets occupy deep basins, and cannot slide down a plane. Furthermore glacial flow depends on stress (including the important yield stress) as well as temperature, and much of the ice sheets are well below melting point.

The accumulation of kilometres of undisturbed ice in cores in Greenland and Antarctica (the same ones that are sometimes used to fuel ideas of global warming) show hundreds of thousands of years of accumulation with no melting or flow. Except around the edges, ice sheets flow at the base, and depend on geothermal heat, not the climate at the surface. It is impossible for the Greenland and Antarctic ice sheets to 'collapse'.

In these days of alarmist warnings about climate warming, the ice sheets of Greenland and Antarctica have an important role. Many papers have described their melting at the present times, and dire predictions of many metres of sea level rise are common. Christoffersen and Hambrey published a typical paper on the Greenland ice sheet in *Geology Today* in May, 2006.

Their model, unfortunately, includes neither the main form of the Greenland Ice Sheet, nor an understanding of how glaciers flow. They predict the behaviour of the Ice Sheet based on melting and accumulation rates at the present day, and the concept of an ice sheet sliding down an inclined plane on a base lubricated by meltwater, which is itself increasing because of global warming. The same misconception is present in textbooks such as *The Great Ice Age* (2000) by R.C.L. Wilson and others, popular magazines such as the June 2007 issue of *National Geographic*, and other scientific articles such as Bamber et al. (2007), which can be regarded as a typical modelling contribution. The idea of a glacier sliding downhill on a base lubricated by meltwater seemed a good idea when first presented by de Saussure in 1779, but a lot has been learned since then.

In the present paper we shall try to show how the mechanism of glacier flow differs from this simple model, and why it is impossible for the Greenland and Antarctic Ice Sheets to collapse. To understand the relationship between global warming and the breakdown of ice sheets it is necessary to know how ice sheets really work. Ice sheets do not simply grow and melt in response to average global temperature. Anyone with this naïve view would have difficulty in explaining why glaciation has been present in the southern hemisphere for about 30 million years, and in the northern hemisphere for only 3 million years.

A glacier budget

In general glaciers grow, flow and melt continuously. There is a budget of gains and losses. Snow falls on high ground. It becomes more and more compact with time, air is extruded, and it turns into solid ice. A few bubbles of air might be trapped, and may be used by scientists to examine the air composition at the time of deposition. More precipitation of snow forms another layer on the top, which goes through the same process, so the ice grows thicker by the addition of new layers at the surface. The existence of such layers, youngest at the top and oldest at the bottom, enables the glacial ice to be studied through time, as in the Vostok cores of Antarctica, a basic source of data on temperature and carbon dioxide over about 400,000 years.

When the ice is thick enough it starts to flow under the force of gravity. A mountain glacier flows mainly downhill, but can flow uphill in places, as in the rotational flow that creates cup-shaped cirques. In an ice sheet the flow is from the depositional high centre towards the edges of the ice sheet. The flow of ice is generally slow, as expressed in the common metaphor "glacially slow", but the rate is variable. The Upernivek Glacier in Greenland flows at about 40 metres per day, which is as much as a smaller Alpine glacier covers in a year.

When the ice reaches a lower altitude or lower latitude where temperature is higher it starts to melt and evaporate. (Evaporation and melting together are called ablation, but for simplicity we shall use 'melting' from now on). If growth and melting balance, the glacier appears to be 'stationary'. If precipitation exceeds melting the glacier grows. If melting exceeds precipitation the glacier recedes.

How glaciers move

Flow is mainly by a process called creep, essentially the movement of atoms from one crystal to another. The first clues to this came from the study of lake ice, which can flow at a stress much lower than the shear strength of 'regular' ice if the stress is applied parallel to the lake surface. This results from the crystal properties of ice. Ice is a hexagonal mineral with glide planes parallel to the base. Lake ice is almost like a sheet of columnar basalt, with the c-axes vertical and the glide planes all parallel to the lake surface, so a push parallel to the glide planes deforms the ice readily. Much greater stress is needed to deform ice perpendicular to the glide planes.

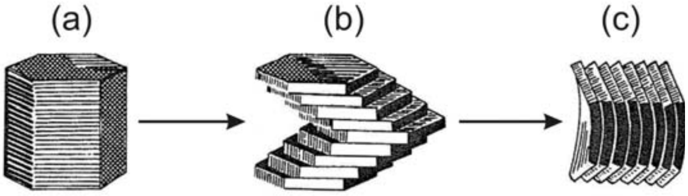

Fig. 1. (a) Hexagonal ice crystal with glide planes parallel to the base. In lake ice the c-axes of the crystals are vertical and the glide planes parallel to the water surface. (b) Crystal deformed plastically by shear stress parallel to the glide planes. (c) Elastic deformation of crystal by strain normal to the glide planes.

Another method of flow is important in 'regular' ice. There is constant gain-and-loss of atoms between different crystals in a mass of ice, and in the absence of any stress an individual grain of ice will lose about the same number of atoms that it gains, and so remain unchanged. But if a crystal is stressed it will lose more atoms than it gains and so shrink, while a nearby unstressed grain will gain more than it loses and so grow. In this way there will be preferential growth of those ice crystals which are oriented in such a way that their glide planes are parallel to the stress, and grains in other orientations will tend to disappear. This is observed in glaciers, where it is found that not only does a marked crystal orientation appear with distance down-valley, but the ice crystals at a glacier snout may have a volume about a thousand times greater than that of the first-formed ice crystals at the source of the glacier. These observations cannot be explained by mechanisms that ignore the crystal structure of ice.

The flow of material in a solid crystalline state is known as creep.

There are three laws of creep relevant to the flow of ice:

1. Creep is proportional to temperature.
2. Creep is proportional to stress (essentially proportional to the weight of overlying ice)
3. There is a minimum stress, called the yield stress, below which creep does not operate.

All these laws have significant effects on glacier movement, and on how glacial behaviour might be interpreted. Alpine glaciers differ significantly from ice caps like Greenland and Antarctica, even though the laws of physics remain the same, and care is needed to transfer knowledge of one kind of glacier to the other.

Creep is proportional to temperature

The closer the temperature comes to the melting point the greater the creep rate. In experiments at a fixed stress it was found that the creep rate at -1°C is 1000 times greater than at -20°C. In valley glaciers the ice is almost everywhere at the prevailing melting point of ice, because the latent heat of ice is very much greater than its specific heat. Very little heat is required to raise the temperature of an ice block from -1°C to 0°C; it takes about 80 times as much heat to turn the same ice block at 0°C into water at 0°C.

Because the temperature does not vary in valley glaciers they are not affected by this first law of creep. But ice caps are very different. They are cooled to temperatures well below freezing point, which reduces their capacity to flow very greatly. Ice caps can be kilometres thick, and their warmest part is actually the base, where the ice is warmed by the Earth's heat, and where flow is concentrated. The drilling of the Northern Greenland Ice Core Project (NGRIP) was stopped by relatively high temperatures near the base and new equipment had to be designed to drill the core from 3001 m to 3085 m. Because ice flows only at the base, great thicknesses of stratified ice can accumulate, as revealed in the ice cores.

The reports about some Greenland cores claim no flow at all! This is presumably the result of cold-based ice. A large geomorphology literature describes delicate landforms such as tors and patterned ground in areas that were formerly covered by an ice sheet. The general view is that cold-based ice essentially preserves any pre-existing landforms, and the erosion potential of cold-based ice is zero or minimal. Importantly for ideas of 'collapse', the ice is not sliding. Indeed it is not moving at all.

Greenland differs from Antarctica in that the ice sheet spills out through gaps in the mountain rim, and the glaciers overlie deep narrow valleys. According to van der Veen and others such valleys have higher than usual geothermal gradients, so it might be geothermal heat, rather than global warming, that causes some Greenland glaciers to have higher than usual flow rates. The overspills have some of the characteristics of alpine glaciers, where evidence of glacier recession is more obvious. In many parts of the world glaciers have been receding since 1895 and with increasing pace since 1930. There is no obvious explanation for this and these dates have no clear counterpart in temperature or carbon dioxide records.

Creep is proportional to stress

Stress in this context is essentially proportional to the weight of overlying ice. This means that the thicker the ice the faster the flow, but a great stress is required if the ice is very cold. This is shown by the huge thicknesses of ice that are undisturbed, as revealed by the ice cores that are used to work out palaeoclimates. In Antarctica, in the Vostok cores the undisturbed ice that provides the desired information continued to a depth of 3310 m or 414,000 years, but below this the ice starts to be deformed.

There is a minimum stress, the yield stress, below which creep does not operate

At the surface there is no stress, so the ice does not flow. However, at a certain depth the weight of ice is sufficient to cause flow, and all the ice below this limit must flow. The threshold boundary between non-flowing ice and flowing ice marks the yield stress level. The brittle upper ice is a solid being carried along on plastic ice beneath. In a valley glacier there is frictional drag at the base and sides, so the maximum flow is somewhere in the middle. This was proved long ago by placing stakes or stones in a line across a glacier, and noting how those in the middle moved furthest. Since the flow is uneven the solid, brittle ice is broken up by a series of cracks called crevasses. The base of crevasses marks the position of the yield stress and the transition from brittle to plastic ice.

In Antarctic and Greenland ice sheets crevasses occur where the ice is flowing towards the edge, but not in the areas of accumulation.

Some results of the laws of glacier flow

These simple rules of creep allow us to understand some observations on glaciers.

Glacial surges

The speed of valley glaciers has been measured for a long time, and is rather variable. Sometimes a valley will flow several times faster than it did earlier. Suppose we had a period of a thousand years of heavy precipitation. This would cause a thickening of the ice, and more rapid glacial flow. The pulse of more rapid flow would eventually pass down the valley. It is important to understand that *the increase in flow rate is not related to present day air temperature, but to increased precipitation long ago.*

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Melting and climate

On July 21, 1983, the lowest reliably measured temperature ever recorded on Earth was at Vostok with -89.2 °C. The highest recorded temperature at Vostok is -19° C, which occurred in January 1992, and during the month of July 1987 the temperature never rose above -72.2° C. At these temperatures ice cannot flow under the pressures that prevail near the surface. Warming has no effect at such low temperatures because ice will not flow faster at -60°C than at -70° C.

In the case of ice sheets it may take many thousands of years for ice to flow from the accumulation area to the melting area. That is why meteorites such as the one from Antarctica that was thought to contain Martian fossils take thousands of years to reach places where they can be collected from the surface. The balance between movement and melting therefore does not relate to today's climate, but to the climate thousands of years ago.

Glaciers and precipitation

We have seen that glaciers and ice sheets are in a state of quasi-equilibrium, governed by rates of melting and rates of accumulation. For a glacier to maintain its present size it must have precipitation as snowfall at its source. This leads to a slightly complex relationship with temperature. If the regional climate becomes too dry, there will be no precipitation, so the glacier will diminish. This could happen if the region became cold enough to reduce evaporation from the ocean. If temperatures rise, evaporation is enhanced and so therefore is snowfall. Paradoxically a regional rise of temperature may lead to increased growth of glaciers and ice sheets. Today, for example, the ice sheets of both Antarctica and Greenland are growing by accumulation of snow.

Icebergs

Where ice sheets or individual glaciers reach the sea, the ice floats and eventually breaks off to form icebergs. This is inevitable so long as glaciers reach the sea. In the southern hemisphere Captain Cook saw icebergs on his search for the great south land. Icebergs have long been familiar to sailors in the northern hemisphere, and the Titanic struck one that had drifted farther south than usual in 1912. The actual break is inevitably a sudden event which can be built into a typical Greenhouse-Horror scenario. Early in 2007, when a piece of the Greenland ice shelf broke away, the scientists interviewed all said they were surprised at how suddenly it happened. How else but suddenly would a piece of ice shelf break off? And this was an area that was ice-free before the Little Ice Age. Arctic explorers used to get their ships a lot closer to northern Greenland than you can now.

The point to remember is that the release of icebergs at the edge of an ice cap does not in any way reflect the flow of ice in the deep interior basin.

The age of ice sheets

In the Greenland ice sheet several cores have more than 3 km of undisturbed ice which go back in time for over 105,000 years, much less than the Antarctic equivalent. The Vostok cores in Antarctica provide data for the past 414,000 years before the ice starts to be deformed. Dome F core reached 3035 m and Dome C core 3309 m, and both date back to 720,000 years. The Epica core in Antarctica goes back to 760,000 years, as does the Guliya core in Tibet. But what is more important than the age is that vast thicknesses of ice are preserved, and they retain complete records of deposition, in spite of the fact that temperatures at times during that period have been warmer than now. They do not fit the model of surface melting, either now or then. After three quarters of a million years of documented continuous accumulation, how can we believe that right now the world's ice sheets are collapsing!

The collapse of ice sheets

Some of the present-day claims that ice sheets 'collapse' are based on false concepts. Ice sheets do not melt from the surface down - they melt only at the edges. Once the edges are lost, further loss depends on the rate of flow of the ice. The rate of flow of ice does not depend on the present climate, but on the amount of ice already accumulated, and that will keep it flowing for a very long time. It is possible that any increase in temperature will cause increased snowfall thereby nourishing the growth of the ice sheet, not diminishing it.

The very ice cores that are used to determine climates over the past 400,000 years also show that the ice sheet has accumulated over that period by stratigraphic layers of snow, and has not been deformed or remelted. The mechanism portrayed by Christoffersen and Hambrey, of meltwater lakes on the surface finding their way down through cracks in the ice and lubricating the bottom of the glacier is not compatible with accumulation of undisturbed snow layers. It might conceivably work on valley glaciers, but it tells us nothing of the 'collapse' of ice sheets.

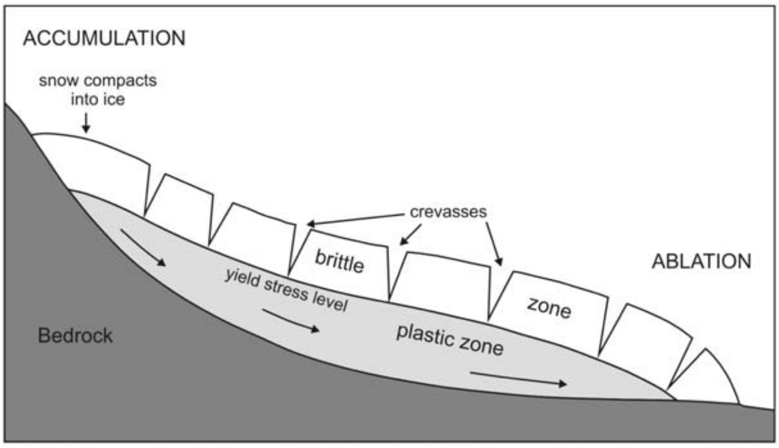

Fig. 2. Diagrammatic long section of a glacier showing the effect of yield stress. Ice stressed beyond yield stress will flow plastically; ice with stress below yield stress will remain brittle, so motion forms cracks (crevasses).

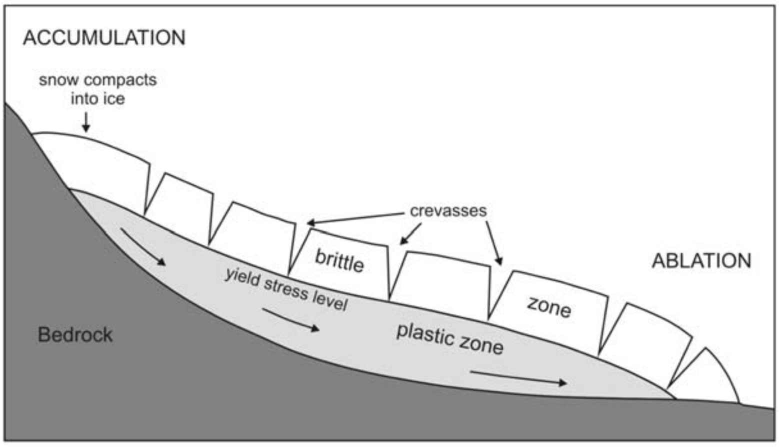

Fig. 3. The analogy of a continental margin with a glacier. Erosion inland and deposition offshore cause isostatic adjustment, which indicates flow in the plastic zone at depth. The upper, brittle zone may be faulted.

Geological associations

This discussion of ice sheets raises two other geological matters.

Continents and ice sheets

It may be helpful for geologists to compare the general structure of continents with that of ice sheets (Figures 2 and 3). Both have a brittle zone over a plastic zone. In valley glaciers the lower zone is flowing by plastic flow, and the upper part is carried along as a brittle body. As the flow is faster in the centre than at the edges stresses are set up that cause the ice to break up. The cracks are crevasses. The depth of the bottom of the crevasses marks the threshold boundary between brittle and plastic zones. In continents brittle tectonics dominates the upper part of the crust, but the lower part may flow. This is the realm of gneisses and schists. Of course, glacier ice is a mono-mineralic metamorphic rock.

Ice sheet basins

Another problem of the Greenland and Antarctic ice sheets is this: Did the ice sheet fill a pre-existing basin, or did the weight of the ice create the basin?

It is generally assumed that the increasing weight as an ice cap grows will cause an isostatic sinking of the underlying rocks, and ever-increasing thickness of ice will cause ever more subsidence.

Alternatively, since many continents have mountains on their edges and lowlands in the middle (Fig. 4), Antarctica and Greenland may have had a similar depression even before ice started to accumulate. An initial basin would provide ideal conditions for the collection of ice if the climate was right. Isostasy could enhance the effect, but does not have the problem of initiating it. This idea might be relevant to the problem of why the Canadian and Scandinavian ice sheets melt frequently while the Greenland and Antarctic ones do not. The former do not have a deep basin in which ice can accumulate and gain sufficient thickness to cause isostatic feedback.

The reverse scenario is that melting of an ice sheet will cause uplift of the land. This is happening in Hudson's Bay and Scandinavia. Stockholm is rising at about a millimetre per year, and Viking ports are now up to 9 km inland. This isostatic response means that the crust must be flowing at depth, in the plastic zone, by creep. Creep in the mantle takes time, so Scandinavia is still rising, thousands of years after the ice load was removed. In the same way the flow of ice-caps is responding to the ancient build-up of potential energy, despite current melting at the ice front. The melting of a few decades is no indication of 'collapse' of the ice sheets.

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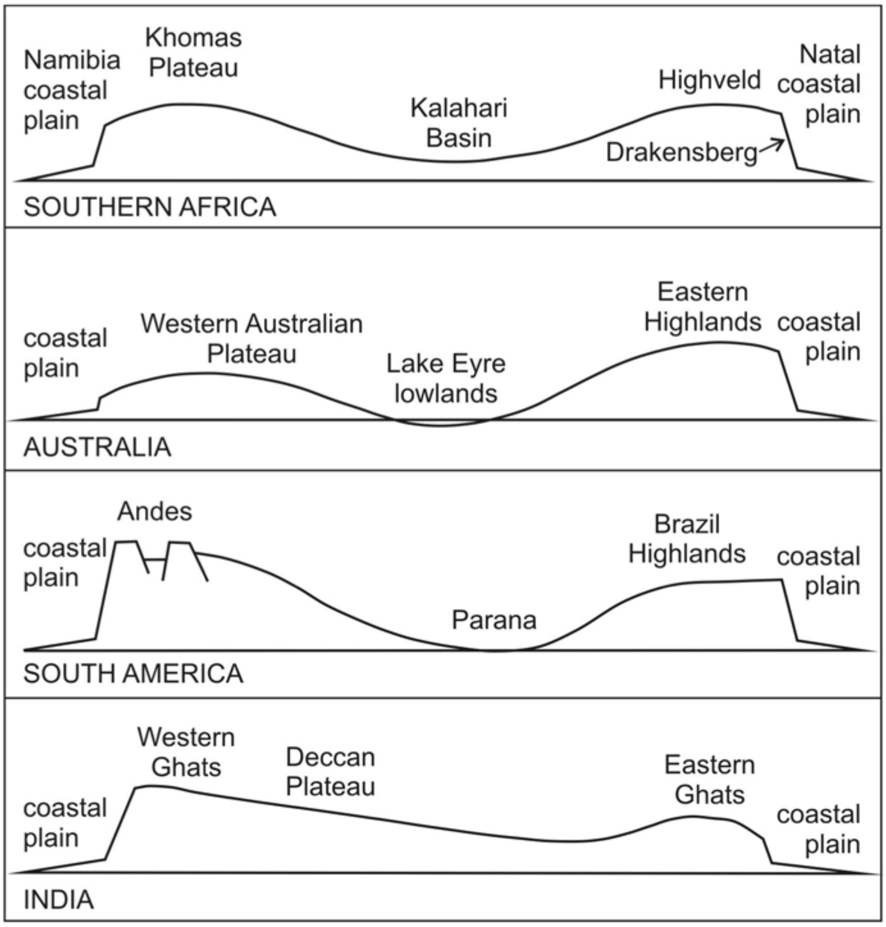

Fig. 4. Simplified cross sections of continents showing that a central depression may be a general feature. Greenland and West Antarctica are roughly similar to the Southern Africa in cross section, but with an ice cap in the depression.

Conclusion

The global warming doomsday writers claim the ice sheets are melting catastrophically, and will cause a sudden rise in sea level of many metres. This ignores the mechanism of glacier flow which is by creep: glaciers are not melting from the surface down, nor are they sliding down an inclined plane lubricated by meltwater. The existence of ice over 3 km thick preserving details of past snowfall and atmospheres, used to decipher past temperature and CO_2 levels, shows that the ice sheets have accumulated for hundreds of thousands of years without melting. Variations in melting around the edges of ice sheets are no indication that they are collapsing. Indeed 'collapse' is impossible. ▲▲

Suggestions for further reading

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