Are the Greenland and Antarctic Ice Sheets in Danger of Collapse?

By
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Greenland (Credit: NASA/SVS)

Antarctica (Credit: NASA/SVS)

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Introduction

Much has been made of a possible precipitous collapse of the Greenland and West Antarctic ice sheets due to manmade climate change and the catastrophic sea level rise if such a collapse were to occur.

Recently, my attention was drawn to a Working Paper by Alan Carlin (2007), which was basically about how emissions reductions may be a dangerous strategy to avoid climate change. Carlin sounds the alarm about climate change, claiming that, "The long standing concern about dangerous climate changes is that there may be a 'tipping point' where a continued rise in global temperatures will trigger non-linear, self-reinforcing further warming or other dangerous environmental effects beyond those resulting immediately from the temperature rise itself."

Carlin argues that the collapse of the major ice sheets is one of the most serious threats we face. He bases his discussion of this perceived threat on papers by Hansen (2007) and others who propose rapid melting of the Greenland and West Antarctica (henceforth Antarctica) Ice Sheets that would lead to a sea level rise of five meters or more. Carlin notes that, "Hansen et al. believe that the most likely and most critical of these dangerous effects is the possibility of substantial sea level rise due to the breakup of parts or all of the ice sheets covering Greenland and West Antarctica."

Hansen's scenario is not reasonable. Indeed, it is not even possible. Hansen's seeming ignorance of the mechanism by which glaciers flow leads him into major errors. In this paper, I will describe glacier dynamics, such as the glacier budget, how glaciers flow (through a process known as "creep"), how creep is related to temperature and stress, and how the simple rules of creep allow us to understand some observations of glaciers.

Hansen's Glacier Model is Wrong!

Hansen is a modeler, and his scenario for the collapse of the ice sheets is based on a false model. His model has the ice sheet sliding along an inclined plane, lubricated by meltwater, which is increasing because of global warming. The same model is adopted in many copycat papers. Christoffersen and Hambrey (2006) and Bamber et al. (2007) are typical. A popular article based on the same flawed model appeared in the June 2007 issue of *National Geographic* and the idea is present in textbooks such as *The Great Ice Age* (2000) by R.C.L. Wilson et al.

Unfortunately, Hansen's model includes neither the main form of the Greenland and Antarctic Ice Sheets, nor an understanding of how glaciers flow. The predicted behavior of the ice sheets is based on melting and accumulation rates at the present day, and on the concept of an ice sheet sliding down an inclined plane on a base lubricated by meltwater, which is itself increasing

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because of global warming. 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.

It is not enough to think that present climate over a few decades can affect the flow of ice sheets. 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 three million years.

To understand what is possible, it is necessary to know something about the physics of glacier flow, which explains a few things not accounted for in the Hansen model, including:

- Why are ice crystals at the foot of a glacier a thousand times bigger than those in the snow that feeds them?
- Why does lake ice deform at lower stress than other ice?
- Why do crevasses only reach a limiting depth?

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 kilometers 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."

A Glacier Budget

In general glaciers grow, flow, and melt continuously, with 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 later 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, 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. In an ice sheet the flow is from the depositional high center towards the edges of the ice sheet. 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 I 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 below 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 (see (a) in Figure 1). Lake ice is a sheet of crystals 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 (See (b) in Figure 1). Much greater stress is needed to deform ice perpendicular to the glide planes (see (c) in Figure 1).[2]

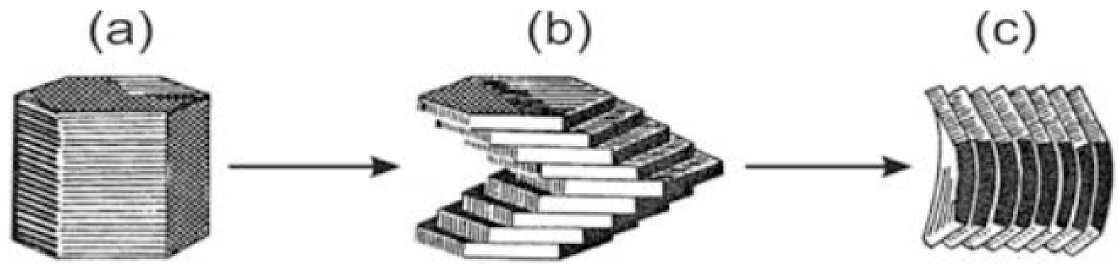

Figure 1. *(a) Hexagonal ice crystal with glide planes parallel to the base. In lake ice the c-axes of the crystals are vertical and the glide planes parallel to the water surface. (b) Crystal deformed plastically by shear stress parallel to the glide planes. (c) Elastic deformation of crystal by strain normal to the glide planes. Grains in such orientation lose molecules to less stressed crystals, which grow bigger. This is why ice crystals grow bigger towards to toe of the glacier, a feature not explained if the ice simply slid along its base.*

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 that 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 a preferred crystal orientation appears with distance down-valley and the ice crystals at a glacier snout 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.

[2] How can a solid flow? In the case of ice it does so by a process called creep, which was not understood until the days of X ray crystallography. Ice crystals are rather like a pack of cards that can slide over each other readily. In lake ice the glide planes are all parallel to the lake surface, and such ice deforms at low stress. If a crystal is not in a position to glide, atoms jump from the most stressed crystals to less stressed crystals, so the latter grow bigger.

Figure 2: *A glacier snout is the lowest end of a glacier, also known as the glacier terminus or toe. This is a Glacier at the head of Canon Fiord, Ellesmere Island, Canada (Source: National Snow and Ice Data Center).*

The flow of material in a solid crystalline state is known as creep, and 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. Alpine glaciers differ significantly from the ice caps of Greenland and Antarctica, and care is needed to transfer knowledge of one kind of glacier to the other. Incidentally, the physics of ice as described here was worked out over 60 years ago by people such as Perutz (1940)

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 minus 1 degree Celsius is 1000 times greater than at minus 20 degrees Celsius. In valley glaciers (glaciers that form in the valleys of mountains, see Figure 3), 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 minus 1 degree Celsius to zero degrees Celsius; it takes about 80 times as much heat to turn the same ice block at zero degrees Celsius into water at zero degrees Celsius. Since the temperature does not vary in valley glaciers, this first law of creep does not affect them.[3]

[3] Ice flows fastest when near the melting point. In alpine (or valley) glaciers and at the edge of ice sheets the ice is all close to melting point, but in the center of ice sheets the temperature is very much below melting point, and flow is absent or very slow.

Figure 3: *Valley glacier in northcentral Chugach Mountains, Alaska (Source: USGS).*

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 kilometers thick, and their warmest part is actually the base, where the ice is warmed by the Earth's heat, and where flow is concentrated. This was evidenced by the fact that drilling by the Northern Greenland Ice Core Project (NGRIP) was stopped by relatively high temperatures near the base. New equipment had to be designed just to drill the core from 3001 meters to 3085 meters. It is because ice only flows at the base that great thicknesses of stratified ice can accumulate, as revealed in the ice cores.

Some Greenland cores show no flow at all. This is 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: 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 et al. (2007), 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.

Creep is Proportional to Stress (i.e., 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 undisturbed ice revealed by the ice cores that are used to work out paleoclimates. In Antarctica, in the Vostok cores the undisturbed ice that provides the desired information continued to a depth of 3310 meters 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: 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 upper, brittle ice is a solid being carried along on plastic ice beneath. 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 towards the edges, where the ice is flowing, but not in the areas of accumulation. In the middle of the ice sheets there are no crevasses to transmit meltwater to the base of the ice sheet, even if it were present (which is impossible).

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.

Melting and Climate

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

Ice sheets may take many thousands of years to flow from the accumulation area to the melting area. The balance between movement and melting therefore does not relate simply to today’s climate, but to the climate thousands of years ago.

Glaciers and Precipitation

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.

The Age of Ice Sheets

In the Greenland ice sheet, several cores have over three kilometers of undisturbed ice that 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. The "Dome F" core reached 3035 meters and "Dome C" core 3309 meters, 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, even infrequently. 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 – 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 an ice sheet 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 grown over that period by accumulation of stratigraphic layers of snow, and has not been deformed or remelted. The mechanism portrayed by Christoffersen and Hambrey (2006), by which meltwater lakes on the surface find 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.

Conclusion

The global warming doomsayers claim the Greenland and Antarctic ice sheets are melting catastrophically, and will cause a sudden rise in sea level of five or more meters. 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 three kilometers thick, preserving details of past snowfall and atmospheres used to decipher past temperature and carbon dioxide 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.

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