Greenland, or why you might care about ice physics

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Kangerdlugssuaq Glacier

I've been trying this week to get a grip on the science of the Greenland Ice Sheet. It's a complex and poorly understood business, but there seems to be enough meat here that I think it should be on The Oil Drum agenda.

We might do worse than start with with a report from the BBC. They covered a talk at the American Geophysical Union meeting in San Francisco this last week. (I didn't get to go, alas).

> Kangerdlugssuaq Glacier on the east coast of Greenland has been clocked using GPS equipment and satellites to be flowing at a rate of 14km per year. It is also losing mass extremely fast, with its front end retreating 5km back up its fjord this year alone. The glacier "drains" about 4% of the ice sheet, dumping tens of cubic km of fresh water in the North Atlantic.

> "We've seen a 5km retreat of the terminus, we've see an almost 300% acceleration in the flow speed and we've seen about a 100m thinning of the glacier - all occurring in the last one or so years," said Dr Gordon Hamilton, of the Climate Change Institute at the University of Maine.

First, some basic statistics. The CIA reports that Greenland has an area of 2.2 million km² -- slightly more than three times the size of Texas -- and a population of 56,375 humans. Greenland is a self-governing colony of Denmark.

Greenland

A "flat to gradually sloping icecap covers all but a narrow, mountainous, barren, rocky coast". The ice sheet covers about 80% of the land, and contains about 2.5 million cubic kilometers of ice. If all that ice were to melt, it would increase global sea level by about **7m, or 23 feet**.

Until very recently, climatologists thought that, although global warming might melt the icesheet eventually, it would be very unlikely to occur on any timescale that we would care about. As the 2001 IPCC report, *Climate Change 2001: The Scientific Basis*, put the issue:

> For Greenland, estimates of the sensitivity to a 1°C local warming over the ice sheet are close to 0.3 mm/yr (with a total range of +0.1 to +0.4 mm/yr) of global sea level equivalent.

Given warming of a few degrees over Greenland, that's at most a few tens of centimeters of sea level rise due to Greenland ice between now and 2100. That can't be too bad, right?

However, the studies on which this estimate was based assumed that the main things going on with the dynamics of the ice sheet are:

1. Snow falls on it and makes it thicker.
2. In the summer, the top melts, the water runs away, and the sheet gets thinner.
3. The ice flows a little faster or slower depending on the thickness of the sheet.

It's now starting to look like this misses the most important physics.

An interesting paper by Zwally *et al* appeared in Science in 2002 (you can get most Science papers over 12 months old with just a free registration). They monitored the location of a pole stuck in the surface of the ice sheet with a GPS monitor stuck on it over several years. What they discovered is that the pole moved at a fixed steady pace in the winter, but in the summer, there were sudden anomalies were the pole started to move faster, which would then stop again later in the summer. Here's Figure 3 of the paper, with it's original caption:

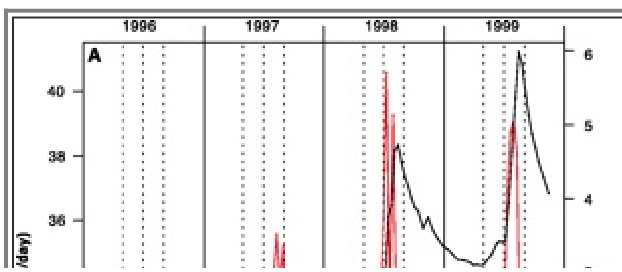
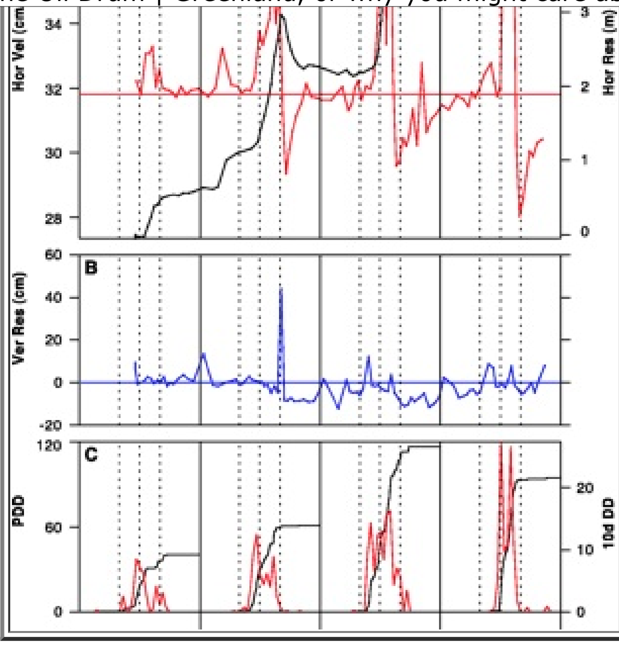


Figure 3. (A) Horizontal ice velocity (red curve) along a smoothed line of motion showing ice accelerations during the summer melt seasons and the abrupt transitions to deceleration around the

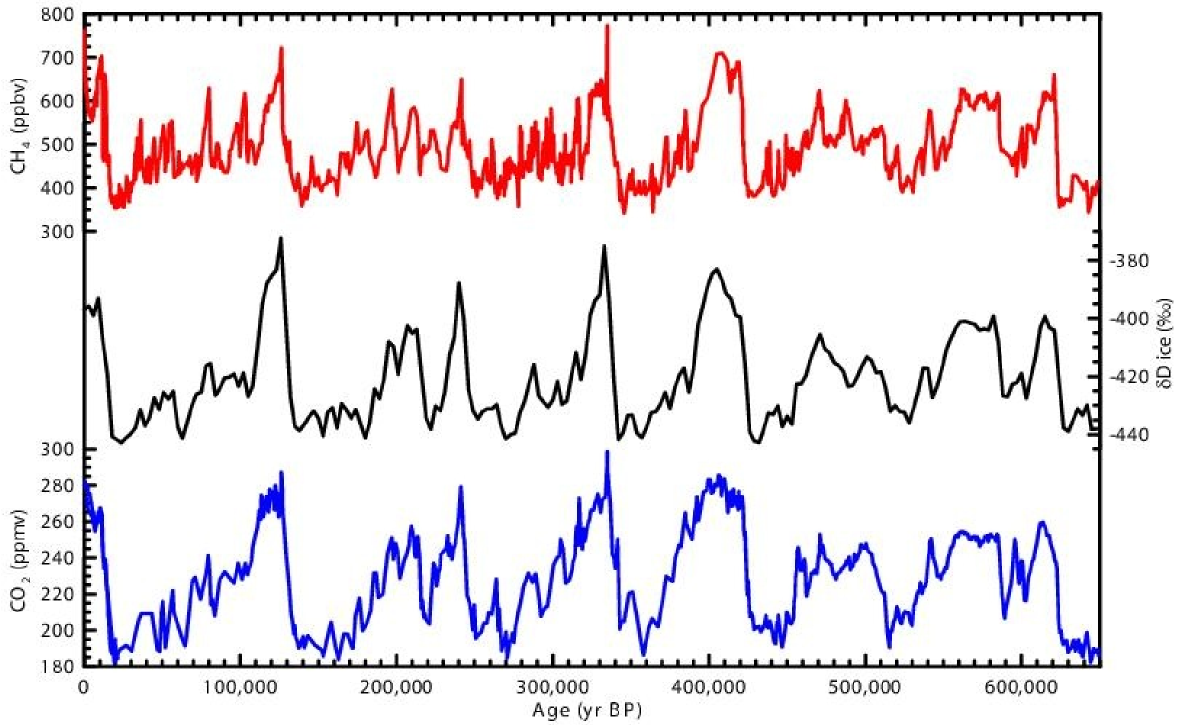


times of melt cessation. The cumulative additional motion (horizontal residual, black) relative to a wintertime-average velocity of 31.33 cm/day is 6.0 m by the time of the maximum velocity in 1999. (B) The vertical residual (blue) indicates a 50-cm uplift at the time of the 1997 transition from accelerating flow to decelerating flow. (C) Cumulative PDDs and PDDs for 10-day intervals (10d DD, red) from temperatures measured at the Swiss Camp, showing correlations of the melting with the intensity and timing of the ice accelerations and decelerations (units are degree-days). Vertical dotted lines mark May 1, July 1, and September 1 for each year.

The picture that emerges is that in the summer, the top of the icesheet starts to melt, this water heads down various vertical channels (moulins) and crevasses, and ends up lubricating the motion of the ice sheet at the bottom, where it grinds against rock. Now, the amount of motion in the Zwally paper is quite small (32 cm/day increasing to 40cm per day), but what is striking is that the effect seems to turn on from almost nothing in less warm years to quite pronounced in warmer years, leading one to wonder how the effect might scale in the future with yet more warmth.

Someone who's been worrying about that a lot is James Hansen, director of the NASA Goddard Institute for Space Studies. In a series of papers (with collaborators) in Scientific American, in Climatic Change, and in Science, he lays out his concerns.

The first thing that needs to be understood is that climate change has been extremely rapid in the past. Recent results from Antarctic ice cores further extend the idea that temperature and composition of key global warming gases vary rapidly at times in the past. This graph covers the last 650,000 years with seven major glaciations in (times when ice sheets cover much of North America and Europe).



CO_2, CH_4, and dueterium percentage (a proxy for temperature) as a function of years before present. Click to enlarge. Source: [RealClimate]

Note in particular that ice ages typically **end** very sharply - eg the most recent one ending 20,000 years ago (the figure is plotted with time going backwards to the right). Now it turns out that this also translates into the ice sheets melting rapidly and sea level rising rapidly.

Sea level rise since the last glacial maximum. Click to enlarge. Source: [Wikipedia]

Over the full 10000 years or so after the icesheets of the last ice age became unstable and started to melt, sea level rose about 120m - a rate of around 1.2m/century. Obviously in the Holocene (the flat sea-level plateau since 8000 years ago), things have been remarkably stable, and it is in that period that humans have built civilization. The remaining Greenland and Antarctic ice sheets have clearly been stable at Holocene temperatures.

The maximum rate of change during the deglaciation occurred during Meltwater Pulse 1A (about 14000 years ago) and was around 5m/century. There is controversy over whether this pulse is primarily due to melting of the ice sheets in North America, or portions of those in Antarctica. However, either way it's an indication that when big ice sheets go, they can go with a rush.

And this is where the worry about Greenland comes in. As Hansen puts it:

> The dominant issue in global warming, in my opinion, is sea-level change and the question of how fast ice sheets can disintegrate. A large portion of the world's people live within a few meters of sea level, with trillions of dollars of infrastructure. The need to preserve global coastlines sets a low ceiling on the level of global warming that would

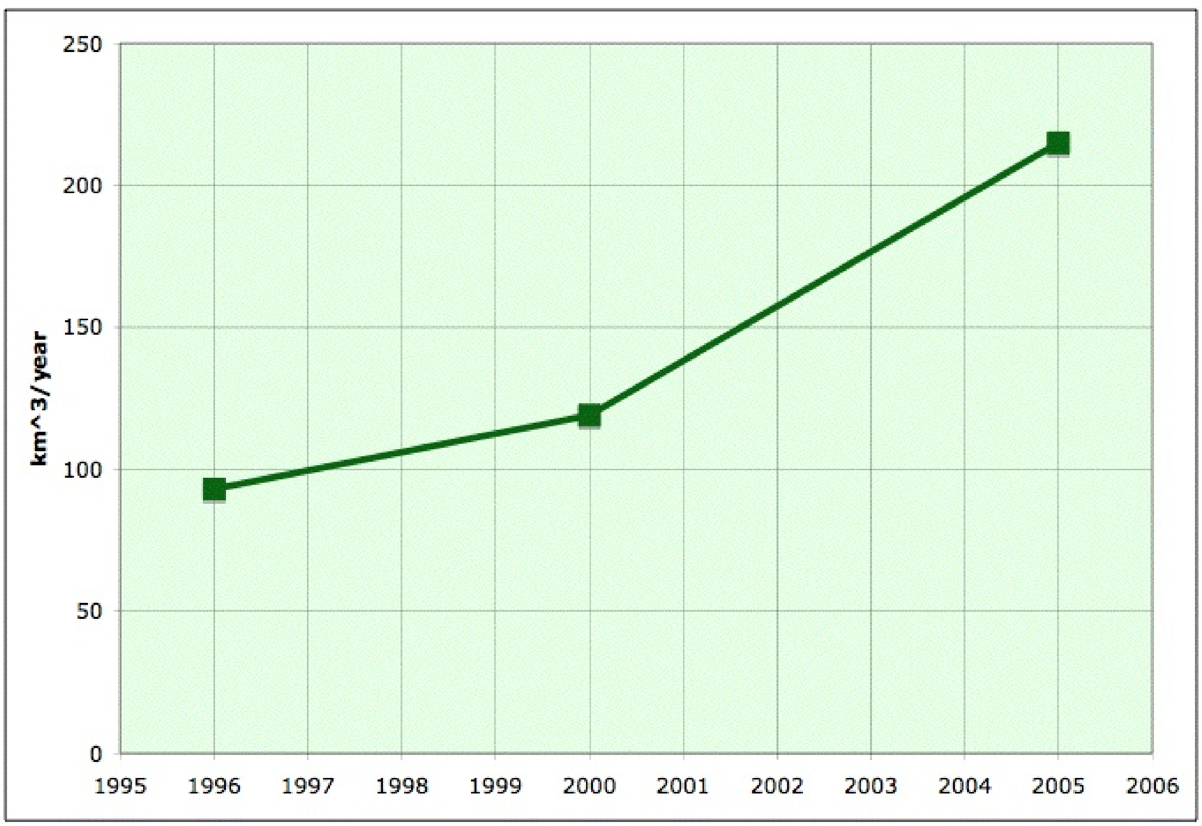
constitute dangerous anthropogenic interference.

The history of the earth and the present human-made planetary energy imbalance together paint a disturbing picture about prospects for sea-level change. Data from the Antartic temperature record show that the warming of the past 50 years has taken global temperature back to approximately the peak for the current interglacial (the Holocene). The is some additional warming in the pipeline that will take us about halfway to the highest global termperature level of the previous interglacial (the Eemian), which was warmer than the Holocene, with sea level estimated to have been five to six meters higher. One additional watter per square meter of forcing, over and above that today, will take global temperature approximately to the maximum level of the Eemian.

The main issue is: How fast will ice sheets respond to global warming?

Given the present unusual global warming rate on an already warm planet, we can anticipate that areas with summer melt and rain will expand over larger ares of Greenland and fringes of Antarctica. Rising seal level itself tends to lift marine ice shelves that buttress land ice, unhinging them from anchor points. As ice shelves break up, this accelerates movement of land to the ocean. Although building of glaciers is slow, once an ice sheet begins to collapes, its demise can be spectacularly rapid.

Since Hansen wrote those words, it has now been tentatively reported from satellite measurements that the net mass loss of Greenland Ice recently is as follows.



Estimated ice mass loss from Greenland in cubic kilometers. Click to enlarge. Source: Real

Climate

This is the quantitative story behind the BBC report that we began with.

Now, compared to the total amount of ice on Greenland -- 2.5 million cubic kilometers -- these are still very small numbers. On the other hand, the volume appears to be growing super-exponentially (ie the doubling time is reducing as we go). If that continues, it won't take many decades for the mass-loss to reach a volume that really matters. On the third hand, you can extrapolate three points just about any way you want. There certainly is **not** scientific certainty that Greenland will melt to an important degree in the twenty-first century. But at this point, scientists are no longer ruling it out, either.

For perspective, here's an EPA map of the portions of the US east coast that would be inundated by 1.5m and 3.5m of sea level rise. 3.5m would be reached halfway through a Greenland icesheet collapse. As you can see, the total area isn't that large, but it includes a pretty large fraction of many of the east coast's coastal cities. That would be expensive.

Areas of the US affected by varying sea level rises. Click to enlarge. Source: EPA

Perhaps the greatest danger is the time lags in the system. There are the time lags in the climate itself - because the ocean is very slow to warm up, the earth still has not reached equilibrium with the greenhouses gases we already have put into the atmosphere. Inbound sunlight is exceeding radiation to space by 0.85+-0.15 W/m^2. The earth probaby has around 0.6 degrees centigrade (roughly 1 degree Fahrenheit) of additional warming just to catch up with what we've already done. But perhaps more importantly, this level of imbalance is believed to be far greater than what drove deglaciations after ice ages in the past. That raises the fear that ice sheets could collapse faster than ice sheets in the past too.

Then there's the time for humanity to swap out it's fossil fuel economy and replace it with whatever we would do instead, which has to be decades at minimum. The big risk is that we will set in motion something unstoppable before we see overwhelmingly clear evidence of it.

At any rate, what is clear is that the Greenland icesheet melting very urgently needs to be understood. In particular in contemplating tar-sands, coal-to-liquids, etc, as solutions to peak oil, we need to understand what gamble with the ice sheet we are making, exactly.