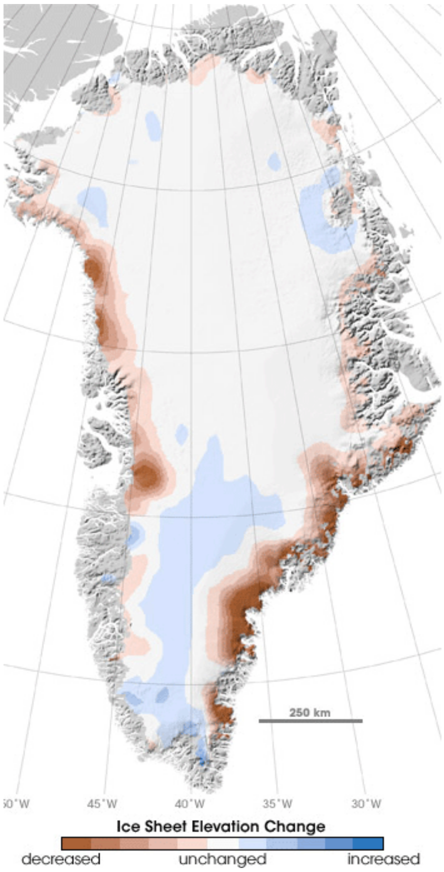

Greenland

Figure 1. *Bright white sea ice reflects almost all of the incoming solar radiation back to space, whereas the dark ocean surface absorbs nearly all of it. Image source: Stephen Hudson / Norsk Polarinstitutt.*

The Greenland ice sheet covers roughly 85% of the land surface of the island and rises to an average height of 2.3 km (1.6 miles). The immense weight of the ice sheet has pushed the center of the island roughly 300 meters (1000 ft) below sea level. The icy expanse of Greenland, like the rest of the Arctic, not only represents an important climatological indicator, it also is critical to future global climate. Were all of Greenland's ice to melt, global sea level would rise 7 meters (23 feet). Greenland's ice sheet is slowly melting due to warming temperatures, and there is great concern that this melting will accelerate and contribute to sea level rise of several feet later this century.

Apart from its potential effect on global sea level rise, Greenland has important regulatory effects on world climate, through its impact on ocean circulation, regional atmospheric circulation, and global heat transfer. The oceanic conveyor belt, or Meridional Overturning Circulation (MOC), is driven by differences in density between salty and fresh water. Greenland's glacial melting dumps fresh water into the ocean, thereby affecting the balance of fresh to salt water and the MOC as a whole. In addition to its effects on the ocean conveyor belt, Greenland also regulates atmospheric temperatures, which affect not only the climate of the island itself, but much of the region as well. Greenland's icy interior functions topographically much like mountain ranges do on land, cooling warm air as it rises as it meets the mountains. Changes to the icy ranges of Greenland will, therefore, affect climactic processes in the region.

Warming temperatures in Greenland and the Arctic will also affect the global climate. The greater the difference in temperature between two places, the faster the heat moves from the warmer to the colder region. As the polar regions become warmer, the temperature difference between the equator and the poles shrinks, making equatorial heat move much more slowly to the poles. However, the flow of heat through the atmosphere from the equator to the poles is what powers global atmospheric circulation. If that flow changes, the path of the jet stream will also be altered, resulting in new storm tracks and precipitation patterns. While some regions will benefit from more favorable rains, others will experience increased drought and water availability problems.

The Interior

Scientists were uncertain until recent years if there had been an increase or decrease in the total amount of water stored in the Greenland ice sheet during the 1990s and early 2000s. However, almost all studies now agree that Greenland is losing mass due to melting, the calving action of glaciers, and sublimation of ice into water vapor. Warmer temperatures in the region have brought increased precipitation to Greenland, and part of the lost mass has been offset by increased snowfall. Determining whether Greenland is melting or gaining mass is difficult, since there are a small number of weather stations on the island. Satellite data can examine the entire island, but has only been available since the early 1990s, making determination of long term trends difficult. According to the 2007 IPCC report (see Figure 4.18),Greenland may have gained as much as 25 gigatons of ice per year between 1961 and 2003--or lost as much as 60 gigatons per year during that period. Between 1993 and 2003, Greenland lost between 50-100 gigatons of ice per year, and had even higher rates of loss between 2003 and 2005.

Despite uncertainty about the mass balance of the Greenland ice sheet, the interior of Greenland is gaining mass (Figure 1). Scientists deduced this by analyzing data collected by European Space Agency satellites that use laser-based altimeters to measure the height of the ice sheet. The sheet has gained an average of 5 cm (2 inches) of snow per year since 1992.[1] This is not a sign that Greenland ice sheet is healthy, though. The extra precipitation falling on Greenland is a result of warming in the region, since there is greater evaporation of water from the oceans and more water vapor present in the atmosphere at warmer temperatures.

In addition to increasing precipitation in the interior, higher temperatures have extended the summer melt season in many places in Greenland. The coastal zones are experiencing the largest increase. In 2005, these areas had up to 20 extra days of melt each year.[2] In 2007, this increased to 25-30 melt days above average. Additionally, the trend extended further inland, affecting a larger area of the southern part of the island than the past (Figure 2). The amount of snow melt at elevations above 2000 meters set a record in 2007.

The Edges

The ice sheet is losing volume from its edges. Glaciers appear to be losing ice at a much faster rate than predicted, and the sides of the ice sheet are losing mass much more quickly than it can accumulate in the interior. This loss is partially due to the increase in runoff from melting caused by warm-weather events, a process called dynamic thinning. Dynamic thinning does not affect all glaciers equally—glaciers lying on top of bedrock that smoothly slopes toward the sea are most strongly affected. Scientists at NASA are currently mapping the topography beneath key glaciers to aid efforts to predict which glaciers are located on slopes conducive to dynamic thinning.[3]

Dynamic thinning is, in a way, a positive feedback loop. When it gets warm enough, the surface snow and ice begin to thaw. The melt water either pools or flows in rivers along the surface, or begins flowing under the snow that covers the ice of the sheet. In the process, it flows into small cracks, enlarging them as it moves towards the bottom of the ice sheet. The amount of melt water traveling through these fissures varies greatly. Waleed Abdalati, head of NASA Goddard Space Flight Centers Cryospheric Sciences Branch, mentioned that "for the first few weeks, the melt water sounds like a peaceful stream. Soon it takes on the menacing roar of a rushing river."[4]

As surface melt increases, it collects into rivers that carry it to turquoise blue pools or plunge into crevasses or ice tunnels called **moulins** or glacier mills. Moulins, like the one in Figure 3, can extend downwards hundreds of meters, reaching the base of the glacier, or can flow within the glacier. Wherever the water ends up, moulins can affect both the melting rate and also the velocity of a glacier. The streams bring surface heat in the form of water down through the glacier to the bottom of the ice sheet. Once the water reaches the bottom of the glacier, it acts as lubrication for the glacier, which then gains speed as it flows downhill towards the sea. Thus, a little melting can have a large effect.

A multinational study that used data collected by a NASA altimeter in its model showed that the combination of dynamic thinning and increased melting from warm weather caused a 35% increase in the annual rate of ice loss in 2003, compared to the period 1993 to 1999.[5] Luthcke *et al.* (2006) reported that the acceleration in the rate at which a number of Greenland's largest glaciers are sliding toward the sea was greater than expected. At the same time, the terminus of the glaciers actually appeared to be retreating due to the rapid melt rates affecting the leading edge.[6] In 2007, which also saw record low sea ice extent in the Arctic, an unprecedented rate of glacial discharge occurred, and melting at the top of the ice sheet approached 150% of its average rate, also a record.[7] These are much higher rates than predicted in the most recent IPCC report, which was based on data from 2005.

Greenland's Kangerdlugssuaq, one of the world's fastest moving glaciers, shows evidence of this trend. About 4% of Greenland's ice flows through Kangerdlugssuaq into the Atlantic. In 2001, the glacier advanced toward the sea at roughly 5km (3 miles) per year. In 2005, however, it had quickened its pace to 14 km (9 miles) per year, and the forward edge had retreated by 10 km (6 miles), its largest retreat on record.[8] High melt rates also affected lower altitude areas in 2007, up 30% from average. Although this isn't record breaking, it is the fifth highest melt rate on record, according to a 2007 NASA study.[9] What is causing all of the recent melting? Well, a big part of the melting is caused by increased sea surface temperatures (SSTs) in the region. Between 1990 and 2011, SSTs warmed by 1 - 2° C (1.8 - 3.6° F) over an extensive region of the waters surrounding Southern Greenland (Figure 4). Much of this increase in SSTs is due to the drastic decline of Arctic sea ice in recent years. Regions near the coast of Greenland that used to see wintertime sea ice are now ice free year-round. With Arctic sea ice expected to continue to decline and possibly disappear in summer later this century, expect SSTs to continue to increase around Greenland.

The Greenland ice sheet has experienced conditions as warm as those today in the past. Chylek *et al.* (2007)[10] found that the area experiencing melting in west Greenland was even greater in the 1930s and 1940s than during the 2000s. Bjork *et al.* (2012) found that the rate of retreat of glaciers that terminated on land in Greenland underwent a more rapid retreat in the 1930s than in the 2000s, whereas marine-terminating glaciers and ice-sheet glaciers retreated more rapidly during the warming of the 2000s. Lowell *et al.* (2007)[11] found organic remains in eastern Greenland that had just been exposed by melting ice, and dated these remains at between A.D. 800 to 1014. Thus, this portion of Greenland was ice-free about 1000 years ago, and temperatures were presumably similar to today's. Erik the Red took advantage of this warm period to establish the first Norse settlements in Greenland around 950 A.D. However, the climate cooled after 1200 A.D., and the Norse settlements disappeared by 1550.

Greenlanders Experience the Visible Effects of a Changing Climate

Figure 3. *Melt water flows into a large moulin in the Greenland ice sheet. Image credit: Roger J. Braithwaite, The University of Manchester, UK. Image Source: NASA.*

The population of Greenland is trying to deal with the effects of a warming planet. A changing climate has many benefits in the eyes of some Greenlanders. For instance, many new fisheries are open now that ocean temperatures are rising. Less ice means safer seas and also allows boats to fish closer to their own shores. In addition, changes in ocean temperature have expanded the ranges of many fish north to the waters around Greenland. Many fishermen are eagerly anticipating huge hauls of cod, which returned to Greenland's waters in 2006. Additionally, halibut, a stock traditionally found in the area, are increasing in size and, therefore, commercial value.

The warming has also made the climate in parts of Greenland similar to that of Northern Europe. Farming on the island, which was previously limited, is now increasing due to a longer growing season and opening of new land to cultivation. Potato and radish crops had bumper years even as far north as Nuuk, only 185 miles from the Arctic Circle. The 2007 growing season marks the first time that Greenlanders have been able to grow broccoli. Carrots and cauliflower are also available from local farms, although all three crops still can't be produced in large enough quantities to feed the population without help from sources in Denmark. A growing number of sheep and cows have appeared, also taking advantage of a longer summer season.

Greenland is experiencing increasing attention for its recently accessible mineral resources, such as gold, oil, diamonds, and gas. There is so much interest in Greenland's mineral resources from abroad, it is possible that Greenland might be able to have a sustainable economy leading to full sovereignty in the near future.

While warmer temperatures have allowed for increased opportunities in fishing and agriculture, there are negative impacts as well. For those who depend on the ice for transportation and platforms for subsistence hunting and fishing, warmer weather is not always welcome. Longer summers mean that there is a shorter amount of time when sea ice is stable enough to allow passage by sled dog or snowmobile. Many communities in Greenland, especially the Inuit communities of the North, have no roads connecting them to the rest of the island. They are dependent upon being able to travel over sea ice. Longer melt seasons and warmer temperatures make the ice precarious for most travelers. A bigger fear is that increased access for boats allowed by melting sea ice will overload fisheries that are not able to handle the stress of heavier harvesting.[12]

When will Greenland be Ice-free?

The sheer volume of water created by the melting of the Greenland ice sheet would cause global sea level to rise 7 meters (23 ft) in total.[13] During the warm period before the most recent ice age, 120,000 years ago, roughly half of the Greenland ice sheet melted. This melting plus the melting of other smaller Arctic ice fields is thought to have caused 2.2-3.4 meters of the 4 - 6 meter sea level rise observed during that period[14]. Temperatures in Greenland are predicted to rise 3°C by 2100, to levels similar to those present during that warm period 120,000 years ago. At those temperatures, a chain of positive feedbacks would lead to the inevitable melting of the ice sheet. As the top of the ice sheet encounters warmer air temperatures, it melts and exposes the underlying layers to the warmer air, lowering the elevation of the island, bringing even warmer temperatures to the ice sheet, since temperatures are cold at high elevations and warmer at low elevations. A 4 - 6 meter rise in global sea level similar to that observed 120,000 years ago would probably result. However, the 2007 IPCC report expects melting of the Greenland ice sheet to occur over about a 1,000 year period, delaying much of the expected sea level rise for many centuries. This means that gradually, over centuries, cities such as London, New York, Shanghai, Boston, and Los Angeles will flood, Florida will be mostly underwater, and countries such as Bangladesh and the Maldives will disappear under the sea. Currently, over one-third of the global population lives in or near a coastal zone. Rising sea levels will dislocate many of them. Additionally, coastal zones are sites of incredible economic and agricultural activity, which would also be negatively affected by higher sea levels. The global impact of these impacts would be "staggering".[15] Additionally, higher sea levels will cause increased erosion, salt water intrusion, and storm surge damage in coastal areas, in addition to a loss of barrier formations such as islands, sand bars, and reefs that would normally protect coastal zones from battering by waves and wind.

Greenland's ice isn't going to be melting completely and catastrophically flooding low-lying areas of the earth in the next few decades. Between 1993 - 2012, sea level rose at about 3.1 mm per year (1.2 inches per decade.) However, the risk later this century needs to be taken seriously. Because of their complexity, many of the processes governing ice melt and formation (especially sea ice) are not incorporated fully into the models that we currently have. This means that agreed-upon estimates of sea-level rise could be too low. In the latest IPCC document released in November 2007, the group acknowledges that their estimated range of sea level rise by 2100 of 0.18-0.59 meters (0.6-1.9 feet) does not "provide an upper bound for sea level rise," and that uncertainties in changes in ice sheet flow could lead to higher sea level rises.[16] The results of coral fossil studies presented by Rohling *et al.* (2007)[13] showed that sea levels rose 1.6 meters (5.3 feet) per century 120,000 years ago, and the climate of that period may be similar to what will be observed in 2100. Greenland's contribution to global sea level rise doubled in the five years ending in 2007 (Stearns and Hamilton, 2007)[17], and was responsible for approximately 10 - 15% of the global annual sea level rise in 2007 (IPCC, 2007, Figure 4.18). By 2012, this percentage had risen to 20 - 25%, and melting ice from Greenland was thought to cause about 0.7 mm/year of global sea level rise, and was on pace to double in ten years (Sasgen *et al.*, 2012.) A study of glacier speeds between 2000 - 2010 (Moon *et al.*, 2012) determined that Greenland's contribution to sea level rise would likely be less than 9.3 cm by 2100, based on the glacier speeds measured in 2000 - 2010. They stated: "Earlier research (Pfeffer *et al.*, 2008) used a kinematic approach to estimate upper bounds of 0.8 to 2.0 m for 21st-century sea level rise. In Greenland, this work assumed ice-sheet-wide doubling of glacier speeds (low-end scenario) or an order of magnitude increase in speeds (high-end scenario) from 2000 to 2010. Our wide sampling of actual 2000 to 2010 changes shows that glacier acceleration across the ice sheet remains far below these estimates, suggesting that sea level rise associated with Greenland glacier dynamics remains well below the low-end scenario (9.3 cm by 2100) at present. Continued acceleration, however, may cause sea level rise to approach the low-end limit by this century's end. Our sampling of a large population of glaciers, many of which have sustained considerable thinning and retreat, suggests little potential for the type of widespread extreme (i.e., order of magnitude) acceleration represented in the high-end scenario (46.7 cm by 2100). Our result is consistent with findings from recent numerical flow models (Price *et al.*, 2011)."

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Related Blogs

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Header: Image of the eastern Greenland coast during the 2007 summer thaw. Modified from NASA Earth Observatory.

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