Changes in Arctic Ice
With Special Focus on Greenland and Sea Level

Testimony of

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*Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect those of the Pennsylvania State University, the Intergovernmental Panel on Climate Change, the National Research Council, or other organizations. My remarks neither prejudge nor presage the contents of Synthesis and Assessment Product 1.2 of the U.S. Climate Change Science Program, now in preparation and for which I am one of the lead authors.

Introduction. My name is Richard Alley. I am Evan Pugh Professor of Geosciences and Associate of the Earth and Environmental Systems Institute at the Pennsylvania State University. I have authored over 175 refereed scientific publications in the areas of ice and climate, which are "highly cited" according to a prominent indexing service, and I have given hundreds of presentations concerning my areas of expertise. My research interests focus especially on glaciers and ice sheets, their potential for causing major changes in sea level, the climate records they contain, and their other effects on the environment. I have been a member of many national and international committees, including chairing the National Research Council's Panel on Abrupt Climate Change (report published by the National Academy Press in 2002) and serving on their Polar Research Board. I have contributed to the efforts of the Intergovernmental Panel on Climate Change (IPCC) in various ways, and served as a Lead Author on Chapter 4 (the Cryosphere), and on the Technical Summary and the Summary for Policymakers of Working Group I of the Fourth Assessment Report, which was released in 2007. I testified to the Committee in February of this year following release of that Summary for Policymakers; here, I will update some of that testimony and provide special focus on the Arctic.

Ice Changes. Recent authoritative assessments from the National Research Council, the Intergovernmental Panel on Climate Change, and other sources have summarized the strong scientific evidence that human activities are altering the composition of the Earth's atmosphere, causing warming and other changes. There exists increasingly strong evidence for widespread reductions in the Earth's ice, including snow, river and lake ice, sea ice, permafrost and seasonally frozen ground, mountain glaciers, and the great ice sheets of Greenland and Antarctica, as summarized by the IPCC and elsewhere. Strong evidence shows the dominant role of warming, which is primarily being caused by human activities, in this loss of ice.

I will briefly summarize some of these many aspects, especially focusing my attention on the issue of ice-sheet shrinkage and its possible effect on sea-level rise. I will rely on my recent testimony to the Committee, summarizing the recent IPCC report, as well as other and more-recent materials as needed.

Snow cover has decreased in most regions, as shown by satellite data tied to limited surface observations. Snow melt is shifting earlier into the spring. Declines in April 1 snowpack have been measured in 75% of western North American sites monitored. As summarized in the IPCC Working Group II report, concerns raised by this decline include the dominant role now played by snowpack in supplying summertime water to many regions of the U.S. West. Trends in snow cover cannot be explained solely by changing precipitation (and indeed, in some very cold places snow depth has increased with increasing precipitation), but much of the overall shrinkage of snow cover can be explained by rising temperature.

Freezing of rivers and lakes generally has been occurring later in the fall, with thawing earlier in the spring, giving longer intervals of open water. Coordinated data collection is scarce, however, and the data set not extensive.

Arctic sea ice, formed by freezing of ocean water, has decreased in area and thickness. The change in the summer has been especially large, with ice lost from an area twice the size of Texas between 1979 and 2005 (decreasing trend in ice area of 7% per decade over that interval). Data sets from satellites, tied to observations from ships and submarines, have been critical in documenting these changes. An especially large loss of sea-ice area was observed during summer of 2007, pushing the late-summer minimum sea-ice area approximately 23% below the previous (from 2005) record minimum documented by satellite, as reported by the National Snow and Ice Data Center (a research institute at the University of Colorado with funding from NSF, NASA, and NOAA). These very recent results were obtained using well-documented techniques that have been detailed in peer-reviewed publications; thus, while full peer-review and assessment of the latest results are not yet completed, the results are generally considered to be highly reliable. Although shifts in circulation of the ocean and atmosphere may have contributed to the ongoing trend of sea-ice loss, greenhouse-gas warming is likely to have been important. (Any Antarctic sea-ice changes fall within natural variability; cooling associated with the ozone hole may be affecting Antarctic climate, a complex subject beyond the scope of these brief remarks.)

Permanently frozen ground (permafrost) and seasonally frozen ground are not readily monitored globally. However, available reports point to overall warming and thawing of this ice in the ground, in response to rising air temperatures and changes in snow cover.

Glaciers and ice caps occur primarily in mountainous areas, and near but distinct from the Greenland and Antarctic ice sheets. On average, the world's glaciers were not changing much around 1960 but have lost mass since, generally with faster mass loss more recently. Glacier melting contributed almost an inch to sea-level rise during 1961-2003 (about 0.50 mm/year, and a faster rate of 0.88 mm/year during 1993-2003). Glaciers experience numerous intriguing ice-flow processes (surges, kinematic waves, tidewater instabilities), allowing a single glacier over a short time to behave in ways that are not controlled by climate. Care is thus required when interpreting the behavior of a particular iconic glacier (and especially the coldest tropical glaciers, which interact with the atmosphere somewhat differently from the great majority of glaciers). But, ice-flow processes and regional effects average out if enough glaciers are studied for a long enough time, allowing glaciers to be quite good indicators of climate change. Furthermore, for a typical mountain glacier, a small warming will increase the mass loss by melting roughly 5 times more than the increase in precipitation from the ability of the warmer air to hold more moisture. Thus, glaciers respond primarily to temperature changes during the summer melt season. Indeed, the observed shrinkage of glaciers, contributing to sea-level rise, has occurred despite a general increase in wintertime snowfall in many places.

Ice-sheet changes. The large ice sheets of Greenland and Antarctica are of special interest, because they are so big and thus could affect sea level so much. Melting of all of the world's mountain glaciers and small ice caps might raise sea level by about 1 foot (0.3 m), but melting of the great ice sheets would raise sea level by just over 200 feet (more than 60 m). We do not expect to see melting of most of that ice, but even a relatively small change in the ice sheets could matter to the world's coasts.

A paper published in the journal *Science* earlier this year (Rahmstorf *et al.*, 2007) compared the projections made in the 2001 IPCC Third Assessment Report to changes that have occurred. The carbon dioxide in the atmosphere has followed expectations closely. Temperature has increased just slightly faster than projected, but well within the stated uncertainties. The central estimate of observed sea-level rise is following near the upper edge of the stated uncertainties of the expectations, however, well above the central estimate. Changes in the ice sheets help explain this.

The 2001 IPCC report noted large uncertainties, but presented a central estimate that the combined response of the ice sheets to warming would be slight net growth averaged over the 21^{st} century, slightly reducing the sea-level rise from other sources, with increase in total snowfall on the ice sheets exceeding increase in total melting and with little change in ice flow. Data collected recently show that the ice sheets very likely have been shrinking and contributing to sea level rise over 1993-2003 and with even larger loss by 2005, as noted in the IPCC report and updated elsewhere (e.g., Alley *et al*., 2007). Thickening in central Greenland from increased snowfall has been more than offset by increased melting in coastal regions. Many of the fast-moving ice streams that drain Greenland (see the Figure, below) and parts of Antarctica have accelerated, transferring mass to the ocean and further contributing to sea-level rise. The total contribution to sea-level rise from the ice sheets remains smaller than the contribution from mountain-glacier melting or from the expansion of ocean water as it warms. However, the existence of the ice-sheet contribution, its important ice-flow source, and the large potential sea-level rise from such mechanisms in the future motivate careful consideration.

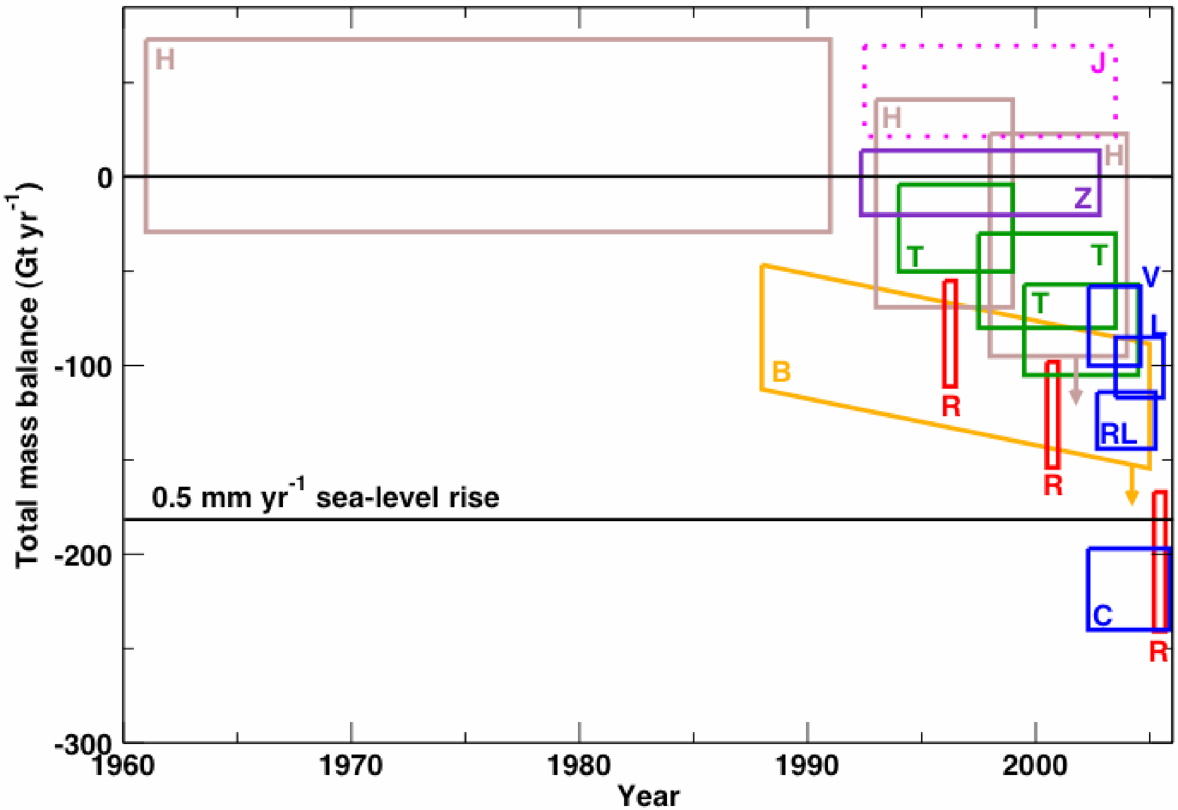
Ice-sheet behavior. An ice-sheet is a two-mile-thick, continent-wide pile of snow that has been squeezed to ice. All piles tend to spread under their own weight, restrained by their own strength (which is why spilled coffee spreads on a table top but the stronger table beneath does not spread), by friction beneath (so pancake batter spreads faster on a greased griddle than on a dry waffle iron), or by “buttressing” from the sides (so a spatula will slow the spreading of the pancake batter). Observations at a site in Greenland have shown that meltwater on top of the ice sheet flows through the ice to the bottom and reduces friction there. More melting in the future thus may reduce friction further, speeding the production of icebergs or exposing more ice to melting from warmth at low altitude, and thus speeding the increase in sea level.

Some early gothic cathedrals suffered from the “spreading-pile” problem, in which the sides tended to bulge out while the roof sagged down, with potentially unpleasant consequences. The beautiful solution was the flying buttress, which transfers some of the spreading tendency to the strong earth beyond the cathedral. Ice sheets also have flying buttresses, called ice shelves. The ice reaching the ocean usually does not immediately break off to form icebergs, but remains attached to the ice sheet while spreading over the ocean. The friction of these ice shelves with local high spots in the sea floor, or with the sides of embayments, helps restrain the spreading of the ice sheet much as a flying buttress supports a cathedral. The ice shelves are at the melting point where they contact water below, and are relatively low in elevation hence warm above. Ice shelves thus are much more easily affected by climatic warming than are the thick, cold central regions of ice sheets. Rapid melting or collapse of several ice shelves has occurred recently, allowing the “gothic cathedrals” behind to spread faster, contributing to sea-level rise. Many additional ice shelves remain that have not changed notably, and these contribute to buttressing of much more ice than was supported by those ice shelves that experienced the large recent changes, so the potential for similar changes contributing to sea-level rise in the future is large.

Although science has succeeded in generating useful understanding and models of numerous aspects of the climate, similar success is not yet available for ice-sheet projections, for reasons that I would be happy to explore with the committee. We do not expect ice sheets to collapse so rapidly that they could raise sea level by meters over decades; simple arguments point to at least centuries. However, the IPCC report is quite clear on the lack of scientific knowledge to make confident projections. Naïve comparison of tabulated projections of sea-level rise in the Third and Fourth Assessment Reports of the IPCC might lead a reader to the mistaken conclusion that the more-recent assessment has reduced uncertainties and concerns about sea-level rise. However, the newer report specifically notes that projections exclude contributions to sea-level change from “future rapid dynamical changes in ice flow” (Table SPM-3) “because a basis in published literature is lacking” (page SPM14), so that it is not possible to “provide a best estimate or an upper bound for sea level rise” (page SPM15). (The new report also notes a similar difficulty arising from lack of knowledge of feedbacks in the carbon cycle, and referring to the possibility that warming will cause much release of methane and carbon dioxide from soils in the Arctic, sediments under the sea, or elsewhere, contributing to more warming.)

Much discussion has focused on the question of “tipping points” or thresholds for abrupt change. Clearly, at sufficiently warm temperatures, ice will melt. As discussed in the IPCC report, sufficiently warm temperature, sustained for a sufficiently long time, will melt the Greenland ice sheet, with more than a few degrees of warming sustained over a few centuries to millennia being a reasonable approximation but with no agreement on exact values. This is often considered to represent a tipping point because a small cooling then would not restore the ice sheet even if sustained for a long time; the warming associated with the loss of the high-elevation and reflective, hence cold, ice surface would overcome any small subsequent cooling. Recent simple modeling (e.g., Schoof, 2007; also see Dupont and Alley, 2005) supports earlier work that “tipping-point” behavior might be observed in Antarctica as well, with warming sufficient to weaken or remove certain ice shelves triggering ice-sheet changes to a new state. These processes remain very poorly understood, and confident assessment of their likelihood or rate is not now possible.

Synopsis. In summary, with high scientific confidence, changes are occurring in much of the world’s ice. These are being caused primarily by warming. Globally, the warming is largely being caused by greenhouse gases being released to the atmosphere by human activities. Shrinkage of the large ice sheets was unexpected to many observers but appears to be occurring, and the poor understanding of these changes prevents reliable projections of future sea-level rise over long times.



Recently published estimates of the mass balance of the Greenland ice sheet through time (modified from Alley *et al.*, 2007). A Total Mass Balance of 0 indicates neither growth nor shrinkage, and -180 Gt yr^{-1} indicates ice-sheet shrinkage contributing to sea-level rise of 0.5 mm/year (1 inch in about 50 years), as indicated. Each box extends from the beginning to the end of the time interval covered by the estimate, with the upper and lower lines indicating the uncertainties in the estimates. A given color is associated with a particular technique, and the different letters identify different studies. Two estimates have arrows attached, because those authors indicated that the change is probably larger than shown. The dotted box in the upper right is a frequently-cited study (Johannessen et al., 2005) that applies only to the central part of the ice sheet, which is thickening, and misses the faster thinning in the margins.

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