# Ice Sheets and Rising Seas

*A big enough rise of global temperatures would eventually melt the world's glaciers, and indeed a retreat of mountain glaciers since the 19th century was apparent in some regions. That would release enough water to raise the sea level a bit. Worse, beginning in the 1960s, several glacier experts warned that part of the Antarctic ice sheet seemed unstable. If the huge mass slid into the ocean, the rise of sea level would wreak great harm, perhaps within the next century or two. While that seemed unlikely (although not impossible), by the 1980s scientists realized that global warming would probably raise sea level enough to damage populous coastal regions.*

Glaciologists, the scientists who study how ice behaves in seriously large quantities, have a special interest in floods. They even have their own word, jökulhlaup (from Icelandic), to describe the spectacular outbursts when water builds up behind a glacier and then breaks loose. An example was the 1922 jökulhlaup in Iceland. Some seven cubic kilometers of water, melted by a volcano under a glacier, had rushed out in a few days. Still grander, almost unimaginably grand, were floods that had swept across Washington state toward the end of the last ice age when a vast lake dammed behind a glacier broke loose. In the 1940s, after decades of arguing, geologists admitted that high ridges in the "scablands" were the equivalent of the little ripples one sees in mud on a streambed, magnified ten thousand times. By the 1950s, glaciologists were accustomed to thinking about catastrophic regional floods.

Also within their purview was flooding on a far grander, but much slower, scale. Since the heroic polar explorations of the late 19th century the world had known that great volumes of water are locked up in ice sheets. If there were substantial melting of the Greenland ice cap, and especially of the titanic volume of ice that buries Antarctica, the water released would raise the oceans in a tide that crept higher and higher for centuries. It had happened before—geologists identified beaches far above the present sea level, cut by waves in warmer periods when the Earth was entirely free of ice. In the last interglacial period, some 125,000 years ago, the planet had reached a temperature about as high as was likely to come from greenhouse warming in the next century or two. Back then, even though most of Antarctica had remained ice-covered, the sea level had been roughly six meters (20 feet) higher than at present. This was about what would be expected if most of Greenland melted. The next time that happened, sea water would swamp coastal regions where a good fraction of the world's population now lived. All this became familiar to anyone who followed scientific discussions of global warming.

Up to the 1960s, if there was any global warming, scientists expected it to steal in over thousands of years, so the threat of flooding lay in a comfortably vague and remote future. To be sure, a few scientists had begun to imagine more abrupt change if the melting of the ice itself brought on conditions that accelerated the warming. Transitions between glacial and warm climates—and back again—might come in a matter of mere centuries. As one example, in 1947 the *New York*

*Times* quoted a prominent Swedish geophysicist, Hans Ahlmann, who suggested that a global warming might be underway that could eventually bring a “catastrophic” rise of sea level as glaciers melted. “Peoples living in lowlands along the shores would be inundated,” he explained, calling on international agencies to undertake studies as an urgent task. Most scientists, however, expected that within the foreseeable future, the main effect of any global warming on ice would be to shrink the icepack on the Arctic Ocean. Since that ice was floating, it could melt entirely away without changing sea level at all.[1]

Glaciers on land could affect sea level, and they were notoriously sensitive to climate. Advances and retreats of glaciers in the Alps in particular had been conspicuous for generations, reacting to small changes not just in temperature but also in the amount of snowfall.[2] In 1962, John Hollin opened up speculation about how relatively small climate changes might also affect ice in Antarctica. He argued that great volumes of ice there, piled up kilometers high and pushing slowly toward the ocean, were held in place by their fringes. These edge sheets were pinned at the marginal “grounding line” where they rested on the ocean floor. A rise of sea level could float an ice sheet up off the floor, releasing the entire stupendous mass behind it to flow more rapidly into the sea.[3]

The idea was picked up by Alex Wilson, who pointed to the spectacle of a “surge.” Glaciologists had long been fascinated by the way a mountain glacier might suddenly give up its usual slow creeping, to race forward at a rate of hundreds of meters a day. They figured this happened when the pressure at the bottom melted ice so that water lubricated the flow. As the ice began to move, friction melted more water and the flow accelerated. Could the ice in Antarctica become unstable in this fashion? If so, the consequences sketched by Wilson would be appalling. As the ice surged into the sea, the world’s sea-coasts would flood. And that would not be the worst of humanity’s problems. Immense sheets of ice would float across the southern oceans, cooling the world by reflecting sunlight. It could bring a new ice age.[4] Hollin joined in with observations of deposits in England that recorded past sea levels, showing rapid rises of as much as ten meters. It

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[1] Gladwin Hill, “Warming Arctic climate melting glaciers faster, raising ocean level, scientist says,” *New York Times*, May 30, 1947. Ewing and Donn (1956a); Budyko (1962).

[2] Glaciers as “sensitive indicators of climate” are stressed in the pioneering theoretical treatment of surges, Nye (1960).

[3] "The chief conclusion of this paper is that the greatest glacial fluctuations in Antarctica were produced by changes in sea-level." The paper was motivated by the idea that the timing of Antarctic glacial movements was set by sea-level changes that reflected Northern Hemisphere glaciation. Hollin (1962), p. 174.

[4] Wilson (1964); Wilson (1966); Wilson (1969); Wilson’s starting-point was the suggestion that the center of Antarctica was at the pressure melting point, see Robin (1962), p. 141, who adds that “one would not expect the ice to surge over a large part of Antarctica at one time”; the role of frictional heat in ice-sheet instability was pointed out back in 1961 (in partial support of Ewing-Donn theory), drawing on earlier work by G. Bodvarsson, by Weertman (1961).

could happen any time, he thought, perhaps in mere decades—or even faster if the sea-level change set off tsunamis. He pointed to unusual features that suggested an abrupt disaster, such as "the curiously intact remains of large mammals" buried whole.[1] Few scientists gave much credence to any of these speculations. The ice that covered most of Antarctica, in places more than four kilometers thick, seemed firmly grounded on the continent's bedrock.

However, in 1968 John Mercer, a bold and eccentric glaciologist at Ohio State University, pointed out a problem — the West Antarctic Ice Sheet. This is a smaller (but still enormous) mass of ice, separated by a mountain range from the bulk of the continent. Mercer argued that this mass was held back, in an especially delicate balance, by the shelves of ice floating at its rim. These shelves might disintegrate under a slight warming. To be sure, that would not raise the sea level, just as the level of water in a glass does not change when a floating ice cube melts. But the much larger mass of ice corked up by the shelves would now be released to slide into the ocean. Just so, Mercer suggested, a collapse of Arctic Ocean ice sheets might have caused the more local, but remarkably sudden, cooling of the North Atlantic around 11,000 years ago that other scientists had identified. A West Antarctic Ice Sheet collapse could be very rapid, Mercer said. The sea level would not rise as far as if all of Antarctica surged, but it would be bad enough—up to five meters (16 feet). Much of the world's population lives near the shore. Such a rise would displace perhaps two billion people and force the abandonment of many great cities. Mercer thought it could happen within the next 40 years.[2]

Mercer published his worries in an obscure conference report, and although he wrote forcefully, he did not push his views on colleagues in the personal encounters that are crucial in a small community of specialists (he much preferred to be out doing fieldwork, often in the nude). The few specialists who heard of his ideas were not impressed. The problem, one of them complained, "could be argued indefinitely if it is not quantized."[3] In fact glaciologists had been working for decades on ways to calculate numbers for the flow of ice masses. In the 1970s they made rapid progress in formulating abstract mathematical models and putting the powerful new computers to work. The calculations, with many approximations, suggested that the West Antarctic Ice Sheet was indeed unstable. Apparently the floating ice shelf that held it back could break up with surprising ease, and the whole mass might begin sliding forward. The idea was backed up by data from adventurous survey expeditions that traversed parts of Antarctica during the 1957-58 International Geophysical Year and on many later occasions. One scientist who

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[1] Hollin (1965), quote p. 15.

[2] Mercer's basic argument was that "fringing ice shelves... will rapidly disintegrate by calving if the average temperature of the warmest month rises above freezing point," Mercer and Emiliani (1970); see Mercer (1968); North Atlantic: Mercer (1969); meanwhile a suggestion about a more gradual disappearance of the Greenland ice cap was advanced by Emiliani (1969); earlier, Robin and Adie (1964), said that catastrophic deglaciation of West Antarctica was "unlikely, but not necessarily impossible," p. 117.

[3] W.J. Campbell in discussion of Wilson (1969), p. 915.

made a landmark calculation, Johannes Weertman, concluded that it was "entirely possible" that the West Antarctic Ice Sheet was already now starting its surge.[1]

The scattering of climate specialists and geologists who paid attention to ice sheets viewed the models as highly speculative. It seemed scarcely possible that anything as massive as the West Antarctic Ice Sheet could disintegrate in less than a few centuries. But if you took a long enough view to be concerned about the next few centuries, a surge that dumped a fifth of a continent of ice into the oceans would be no small thing, and they could not rule it out. The picture fitted with a new feeling that was emerging in the climate community, a feeling that the climate system in general was unstable or even radically chaotic.

Concern sharpened in 1975 when Cesare Emiliani at the University of Miami reported measuring deep-sea cores that showed a shockingly rapid rise of sea level—a rate of meters per decade—around 11,600 years ago. (He remarked that this was exactly the time Plato had given for the fall of Atlantis!) Emiliani thought the cause of the flooding might not have been an Antarctic surge, but water rapidly released from enormous lakes that had been penned up behind the North American ice sheet: a titanic jökulhlaup. In places like Florida where the land sloped gently into the ocean, he wrote, "the sea would have been seen to advance inland 300 feet in... a single summer."[2] Other areas at risk included the Nile Delta and the Netherlands. Science journalists made sure that the more spectacular warnings reached a broad public.[3]

Meanwhile radar surveys from airplanes showed that the ice of West Antarctica moved toward the sea not as a single sheet but through a set of enormous ice streams. Terence J. Hughes (who started out studying metallurgy but moved on to a different sort of solid material) and other glaciologists developed increasingly elaborate models of ice sheet dynamics. They showed how a slight shift in conditions could prompt an ice shelf to break up into flotillas of icebergs.[4] Looking over the new data and theories, Mercer worried that most climate experts still assumed that ice sheet changes would take many centuries. In 1978, he finally caught their attention with an article in the leading journal *Nature*, contending that because of global warming from that humanity's use of fossil fuels, "a major disaster... may be imminent or in progress." Mercer admitted that the computer models were loaded with uncertainties, but "there is, at present, no way of knowing whether they err on the optimistic or the pessimistic side."[5]

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[1] Data were analyzed by Hughes (1973); Weertman (1974), "entirely possible," p. 3; the classic theory was Thomas (1973a); and Thomas (1973b); Flohn (1974) gave a more general model; on ice modeling, see also Hughes (1977).

[2] Emiliani et al. (1975); see *Science* (9/24/76): 1268 for criticism. Quote: Emiliani (1980), p. 87.

[3] E.g., Calder (1975); note also the semi-popular article: Emiliani (1980).

[4] Hughes (1977); Hughes et al. (1977); Thomas and Bentley (1978).

[5] Mercer (1978), quotes pp. 321, 325. On Mercer see Broecker and Kunzig (2008), p. 147.

Mercer, Hollin and Hughes had a chance to argue their case to a group of experts at a meeting convened in April 1979 in Annapolis, Maryland. One participant noted in his diary that their arguments convinced him that the deglaciation of West Antarctica was "a plausible hypothesis." The majority felt that this was "not a cause for immediate alarm however. We are talking about centuries."[1] In a published review, a trio of experts laid out arguments explaining why the collapse of an ice sheet would probably take several centuries to run its course. Yet they admitted that "little is known about the glaciers," and a 5-meter rise in sea level could possibly happen within a century. "Mercer's warning," they concluded, "cannot be dismissed lightly."[2]

That continued to be the most common view through the 1980s. Most studies found that an ice sheet collapse was likely to take centuries rather than decades. But experts knew too little about the behavior of Antarctica's mammoth ice rivers to agree on any firm conclusion. Field glaciologists, a small but hardy group, measured one or another ice sheet as best they could at a few scattered locations. They found ice streams moving at speeds of hundreds of meters a year, far faster than ordinary mountain glaciers. Meanwhile, their mathematically-minded colleagues back home constructed simplified models for the flow.[3] Some studies foresaw the possibility of a sea-level rise of two or three meters (6-10 feet) by 2100, but most found this unlikely so soon. In particular, for a 1983 National Academy of Sciences report, the dean of oceanographers, Roger Revelle, estimated that within the next hundred years the sea level would probably rise some 70 cm (about two feet). That would be harmful but not catastrophic. He did worry, however, about an Antarctic collapse later on.[4]

Some rise of sea level in the coming century seemed not just possible, but nearly certain. The oceans had already risen 10 or 20 centimeters in the 20th century, about ten times as fast as the average sea-level rise in previous millennia. Just where all the water had come from remained uncertain. As one example, it was not until the 1990s that experts realized that significant volumes of water were engaged by human activities like irrigation and building reservoirs, and they could not say whether the net result of such activities was to take water from the oceans or to put more in.[5]

One contribution to the sea-level rise was entirely clear. Water expands when heated. The consequences may seem obvious, but amid all the talk of melting glaciers, for decades nobody seems to have given a thought to other simple effects. Finally in 1982 two groups separately

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[1] Elliott (1977-89), vol. 1, 4/8/79.

[2] Thomas et al. (1979), p. 355.

[3] E.g., Herterich (1987).

[4] Revelle (1983); similarly Thomas et al. (1979); Bentley (1980) saw a possible ice sheet collapse in the next 500 years; but Bentley (1982) said melting could take thousands of years; this was disputed by Hughes (1982); Hollin (1980) tried to demonstrate an East Antarctic ice sheet surge about 95,000 years ago; for predictions of meter-scale rises, see Jones and Henderson-Sellers (1990), pp. 10-11, 15; a skeptic: Van der Veen (1985); Van der Veen (1988).

[5] IPCC (2001), pp. 657-58.

calculated that the global warming observed since the mid-19th century must have raised the sea level significantly by plain thermal expansion of the upper ocean layers. But a thermal expansion could not account for all of the observed rise. The scientists figured the rest came from melting glaciers (most of the world's small mountain glaciers were in fact shrinking).[1]

The rising waters might help the West Antarctic Ice Sheet float off its moorings and slowly break up. Even if that never happened, there would still be problems. Scientists warned that tides would probably mount a half meter or even a meter and a half higher by the end of the next century, bringing severe harm to coastal regions. Beaches would erode back hundreds of feet. Salt water would advance into fragile estuaries. Entire populations would flee from storm surges.[2]

While the calculations of thermal expansion were straightforward, the actual sea level rise would depend on a much tougher problem—what would happen to the ice sheets of Greenland and Antarctica? So long as they did not surge and disintegrate, global warming would not necessarily make them dwindle. A warmer atmosphere would hold and transport more water vapor, so it would drop more snow. Thus the polar ice sheets might actually grow thicker, withdrawing water from the oceans. The future sea level depended crucially on just what happened to glaciers and ice sheets, one pair of experts concluded, and predicting that would be "a daunting task."[3]

## After 1988

To sketch out an answer to the great question of ice-sheet collapse, since the early 1980s scientists had bundled up in parkas and gone out onto the windswept wastes of Antarctica. Their difficult goal was to measure the motions of the immense slow ice currents, using radar pulses, seismic measurements, and boreholes to study how ice moved over the rock beneath. One example was a scientist who had been skeptical of surge models—he recalled that he "felt the whole thing was like a house of cards"—but who changed his mind when he discovered that a kilometer-thick Antarctic ice stream rested not on bedrock but on a layer of slippery mud. Another unsettling discovery was that in recent centuries some of the great ice streams had stopped or started moving, for no clear reason.[4] Far more such data would be needed to bring a definitive answer. The dynamics of ice sheets and the streams that fed them turned out to be, like most things geophysical, a complicated snarl of influences. Experts could not even agree on whether the West Antarctic Ice Sheet had disintegrated during previous warm epochs over the

[1] Etkins and Epstein (1982); Gornitz et al. (1982).

[2] "Most workers" project 0.5-1.5m rise in next 50-100 years if warming continues, according to Schneider (1989b), p. 777; he cites i.a. Meier et al. (1985); this range was taken as plausible for 2100 in National Research Council (1987); but only a few cm rise by 2025 according to the most cited of these papers, Wigley and Raper (1987).

[3] Wigley and Raper (1987), p. 131.

[4] Barclay Kamb quoted by Walker (1999); the slippage was predicted by Blankenship et al. (1986). For this and other history see Bindschadler and Bentley (2002).

past few million years. The past sea level rises might have come from Greenland ice, or from something else entirely. But according to evidence developed in the 1990s, during a dramatic episode at the end of the last ice age, *something* had once raised the sea level 16 meters within three centuries. The rate of rise might have reached two feet per decade. Antarctica was the most likely source of all that water. The rush of new data fed what one observer called “polite but emotional debate” among experts about the future possibilities.[1]

Meanwhile satellite pictures revealed that some of the smaller floating ice shelves poking out from the peninsula that projects from the Antarctic continent were rapidly disintegrating.[2] It was not clear whether the changes had anything to say about the possibility of a catastrophic ice-sheet collapse. In these little-known regions, the changes might have been a type of normal, regional event, which just had not been noticed before the age of intensive global monitoring. Yet the public’s concern about global warming was reinforced from time to time when satellite images showed tabular icebergs bigger than cities floating off. And scientists began to doubt this was normal. After all, back in 1978 Mercer had called for keeping an eye on just these ice shelves, contending that their breakup would be “one of the warning signs that a dangerous warming trend is under way in Antarctica.” He had predicted still more specifically that the collapse of ice shelves would start at the northern end of the Antarctic Peninsula and proceed south, and indeed by 1996 the five most northern ice shelves were shrinking rapidly, but not the more southerly ones.[3]

Specialists in glacier flow worked up increasingly elaborate ice-sheet models. Entirely aside from the question of Antarctic surging, these models might be useful in explaining the ice ages. It seemed increasingly likely that the reason ice sheets came and went in cycles of around 100,000 years had something to do with the length of time needed for a continent of ice to form and flow and melt. Nothing else on Earth seemed to change on the right timescale.

The models failed to answer the question of how fast a major ice sheet could surge into the ocean. The improved models did show, reassuringly, that there was no plausible way for a large mass of Antarctic ice to collapse altogether during the 21st century. According to these models, if the West Antarctic Ice Sheet diminished at all, it would discharge its burden only slowly over several centuries, not placing too heavy a burden on human society. Yet scientists could not altogether rule out the possibility of a shocking surprise in some future generation. The West Antarctic Ice Sheet remained what one expert had called it a quarter-century earlier —“glaciology’s grand unsolved problem.”[4]

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[1] Later work confirmed Antarctic ice as the source: Clark et al. (2002); “debate”: W. Sullivan, *New York Times*, May 2, 1995, p. C4. 16m rise: Bard et al. (1990); Hanebuth et al. (2000).

[2] Doake and Vaughan (1991); Rott et al. (1996).

[3] Mercer (1978), p. 325; Vaughan and Doake (1996).

[4] Oppenheimer (1998); IPCC (2001), pp. 678-79; "Unsolved Problem" was the title of Weertman (1976b); repeated in Van der Veen and Oerlemans (1987), p. 14.

Scientists were still less able to answer the question of whether climate change was gradually melting the rest of the world's glaciers and ice caps, or instead was adding snow to them. In "those huge areas where little or no information is available," an expert explained in 1993, "almost anything might be happening." But in 2005 a survey of mountain glaciers around the world found that most of those for which historical records existed had been shrinking since 1900. Some that had survived for many thousands of years were vanishing, a striking sign of unprecedented climate change. Experts could only speculate how far this might affect sea level, especially if it were counteracted by the increased snowfall that some models predicted global warming would bring in the remote dry highlands of Antarctica.[1]

As scientists turned increasing attention to ice movements, they discovered many kinds of changes, thanks to views from satellites and airplane overflights as well as increasingly precise measurements by grueling expeditions on the ice itself. "Perhaps the most important finding of the past 20 years," a glaciologist reported in 2002, "has been the rapidity with which substantial changes can occur on polar ice sheets." Warmer ocean waters were melting the underside of ice sheets by tens of meters a year, altering where grounding lines pinned them. Entire floating ice shelves, some of which had been in place for thousands of years, were rapidly thinning, or astonishing experts by breaking up completely. Ice streams that had been held behind the disintegrating shelves accelerated.

Most scientists had figured that even after the air got warm enough to melt the surface of an ice shelf, it would take millennia for the entire great mass to melt away. It turned out, however, that meltwater could seep down into crevasses, refreeze there and wedge them wider, prying apart a thick sheet in months. Meanwhile the gradually warming seawater worked to break up the ice from beneath. None of this had been foreseen by the crude computer models of ice behavior.

Modelers scrambled to incorporate the new concepts. Revised computer simulations and further observations confirmed the idea, originally so speculative, that removing an ice shelf could dramatically speed up the drainage of glaciers "corked up" behind it. In 2004 evidence was published that some of the enormous ice streams leading from the West Antarctic Ice Sheet to the ocean were also speeding up. Scientists were no longer sure how many centuries it might take to drain the entire sheet. "The response time scale of ice dynamics is a lot shorter than we used to think it was," admitted a leader of the WAIS research.[2]

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[1] Thomas (1993), p. 398; Oerlemans (1994); Dyurgerov and Meier (2000); Oerlemans (2005) surveyed glacier records around the world and found that "for the period from 1900 to 1980, 142 of the 144 glaciers retreated"; see review by Alley et al. (2005).

[2] NOTE that the papers I cite throughout this section are only examples of numerous papers by these and some other authors. A readable summary is in Broecker and Kunzig (2008), pp. 152-56. Wedging: Doake et al. (1998). Ice base melting: Rignot and Thomas (2002), "most important finding," p. 1505. Other work pointing in the same direction included De Angelis and Skvarca (2003), who found that Antarctic grounded ice surged after an ice shelf breakup, and Bindschadler et al.(2003), who reported that a major West Antarctic ice stream started and

Only a few people were trying to make computer models of any of these processes, and their models remained primitive. A mass of ice is an odd substance, something between a fluid and a solid, no easy thing to simulate. And far too little data had been gathered from the surfaces of these perilous and remote wastes, let alone from their bases. The most modelers could say was that “The latest theoretical advances have done nothing to allay fears concerning the potential instability of marine ice sheets.”[1]

Meanwhile, starting around 2000, a few studies raised the additional possibility that the Greenland Ice Sheet, contrary to what most scientists had figured, might not be comforably stable over the next few centuries. In the warmer summers the snow on the surface would get wet, and become darker. So it would absorb more sunlight and warm still more. Under one speculative scenario, rivers of water would drain through deep holes (“moulins”) straight to the bottom of the ice and lubricate it. That might provide, as one team put it, “a mechanism for rapid, large-scale, dynamic responses of ice sheets to climate warming.” As the flow of its huge ice streams accelerated, the Greenland ice cap would thin around the edges. As the ice surface sank to lower altitudes where the air was warmer, it could melt all the faster. Conceivably, an armada of icebergs would invade the North Atlantic and melt, as had happened around the end of the last ice age. At that time the sea level had risen at a rate that would be catastrophic for coastal areas. The process would presumably take centuries to run its course, if not millennia, but glaciologists could only speculate about the probability and timing of such a misfortune.[2]

Concern sharpened in 2006 when analysis of satellite radar data found that the velocities of large ice streams in southern Greenland had doubled in the past five years — something most experts had thought was impossible. Perhaps the speculations about lubrication of the base of an ice stream were correct? The Greenland ice streams soon slowed down again, but glaciologists were not reassured. Considering how ice streams around Antarctica had also been observed to accelerate and slow down suddenly, it seemed that these systems were more sensitive to perturbations than the scientific community at large assumed. Moreover, a new satellite was

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stopped flowing as the tide went up and down. Breakup of an ice shelf (Larsen) leads to a speedup of glacier movement: Rignot et al. (2004), Scambos et al.(2004) (who also note lubrication by percolating water, see following note).WAIS models: Payne (2004); observed WAIS changes: Thomas (2004), Siegert (2004). Several papers by Rignot and colleagues document other Antarctic changes. “A lot shorter:” Robert Bindschadler in Larry Rohter, “Antarctica, Warming, Looks More Vulnerable,” *New York Times,* 25 Jan. 2005, section D. See Holmes (2004) for discussion.

[1] Vaughan and Arthern (2007).

[2] Concern about Greenland glacier surging was spurred by Krabill et al. (1999). Lubrication: Zwally et al. (2002). For discussion see, e.g., Schiermeier (2004) and Bindschadler (2006). Darkening (notably by melt pools): Curry et al. (1995). “Mechanism:” Shepherd et al. (2004). Hansen raised the issue of iceberg armadas (discussed in the essay on rapid climate change), and went so far as to call the Greenland ice a “ticking time bomb:” Hansen (2005), p. 275.

transmitted disturbing data. It measured gravitational force so sensitively that it could detect changes in the massof an ice sheet from year to year. Both Greenland and West Antarctica were losing substantial amounts of ice.[1]

So far, the mass loss was not enough to make a big difference in the rate of sea level rise. When the authoritative Intergovernmental Panel on Climate Change (IPCC) issued its 2007 report, the authors found the new ideas about ice sheets so uncertain that for their sea level predictions they relied upon old, classic models for ice processes, taking no account of the possibility of surges. Some senior glaciologists worried that ignoring an unknown did not make it go away. They saw a small but serious possibility that ice stream acceleration could add significantly to sea level rise before the end of the century, and a greater chance for that in later centuries. A minority of climate experts argued that it was a mistake to concentrate on what seemed most probable, while ignoring processes that, although not very likely, would be catastrophic if they did come to pass.[2]

At least one thing was certain. If temperatures climbed a few degrees, as climate scientists now considered likely, the sea level would rise simply because water expands when heated. This is almost the only thing about global change that can be calculated directly from basic physics. The additional effects of glacier and ice sheet melting remained highly uncertain (scientists were still arguing over how much of the 20th century's sea level rise was due to heat expansion and how much to ice melting). In 2001 the IPCC had offered a rough guess for the total rise expected by the end of the 21st century — perhaps half a meter, give or take a bit — and the authors of the 2007 report came up with much the same numbers. But even before the new results came in from Greenland and Antarctica, some scientists had been worrying that the rise might be twice that. Now they were still less willing to rule out the possibility of a rise of a meter (a rate observed in some past geological ages), or even substantially more.[3]

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[1] Greenland ice stream acceleration: e.g., Rignot and Kanagaratnam (2006); also, small earthquakes in Greenland, caused by sliding glaciers, had become twice as frequent: Ekström et al. (2006). Slowdown: Howat et al. (2007). Mass loss: e.g., Chen et al. (2006); Luthcke et al. (2006); Zwally et al. (2005); Rignot et al. (2008).

[2] Classical models: notably Huybrechts (1990). The grids in current models are still too coarse to simulate ice streams. On claims of political interference in the IPCC final report see Pearce (2007a) and response by Piers Foster et al., Letter, *New Scientist*, March 24, 2007, p. 26. I also draw here on my own conversations with glaciologists. See Oppenheimer et al. (2007); also Susan Solomon et al. and Michael Oppenheimer et al., Exchange of Letters, *Science* **319** (2008): 409-10.

[3] Despite measurements of total heat absorbed by the oceans by Levitus et al. (2000) and Levitus et al. (2001), "20th-century sea level remains an enigma—we do not know whether warming or melting was dominant, and the budget is far from closed," according to Munk (2003). IPCC (2001) pp. 641-42, projects between 0.1 and 0.9 m rise including ice melting; IPCC (2007b), p. 13 projects 0.2 to 0.6 m *explicitly excluding* possible ice change surprises. See also Meehl et al. (2005) . Rapid sea-level changes (10 meters within 1000 years) were found in ancient coral reefs: Thompson and Goldstein (2005). "A rise of over 1 m by 2100 for strong

A meter may not sound like much, but in many areas it would bring the sea inland a hundred meters or more (a few hundred feet), and even farther if storm-driven surges grow stronger. While such a rise would not be a world disaster, in the late decades of this century it would bring significant everyday problems, and occasional storm-surge catastrophes, to populous coastal areas from Bangladesh to New Orleans. [That last was written in 2002; the following includes later additions.]

Experts had warned for decades that New Orleans was at risk, and some had pointed out that the chance of disaster would mount as global warming raised sea-levels and perhaps increased storminess. But after August 2005 some experts asked whether Hurricane Katrina would have devastated the city, if the heat in the Gulf of Mexico's waters — a main source of the storm's energy — had not been higher than normal? Such a question can never be answered for a single event. The important question is not what global warming did in one case, but what it would mean for the future probability of terrible hurricanes and typhoons.

Scientists had only a sketchy idea of how tropical storms worked. Nevertheless, when the 21st century began, nearly all experts had been confident that tropical storms would not become seriously worse for many decades. (Outside the tropics, computer models indicated that storms might not get worse at all as the world warmed up, although they would shift to different regions.) Even Kerry Emanuel, who had explained in 1987 how a warmer sea surface would provide energy for greater storms, had not expected a noticeable change anytime soon. But when he analyzed decades of data on tropical storms, he found a disturbing trend. While the *number* of hurricanes and typhoons had not been increasing, the *intensity* of the worst storms had climbed in recent decades. The rapid increase in destructive power, so different from what experts had expected, correlated surprisingly well with the observed rise of sea-surface temperatures. "For the first time in my professional career," Emanuel recalled, "I got alarmed." In mid 2005 he wrote a warning of gathering danger. It attracted much attention three weeks later, when Katrina struck.[1]

Meanwhile a separate group had gotten similar results. But other meteorologists stuck by their earlier conclusions. A fervent, sometimes personal controversy broke out. The experts of the old school insisted that the record of tropical storm intensities was only guesswork for most of the 20th century, especially in the vast unvisited spaces of the Pacific. If there had indeed been a change in hurricanes, they supposed it was only a phase in a normal North Atlantic cycle. Computer models varied, some projecting little change, others predicting a modest increase in

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warming scenarios cannot be ruled out," Rahmstorf (2007). The problem will be compounded in many river deltas (Nile, Ganges, Mississippi, etc.) by a half meter or so of subsidence as dams impound sediment and water is withdrawn from aquifers.

[1] "For the first time" quoted Kunzig (2006), p.22. Emanuel (1987); Emanuel (2005a), published 4 Aug., found that "longer storm lifetimes and greater storm intensities... correlated with [higher] sea surface temperatures."

tropical storm intensity by the end of the century. Most onlookers could only conclude that scientific understanding was so limited that, as one group concluded, "the question of whether hurricane intensity is globally trending upwards in a warming climate will likely remain a point of debate in the foreseeable future." The very uncertainty of the matter was a call to action. If there was any risk of increased coastal devastation, that was not something we could leave for the next generation to worry about.[1]

The sea-level rise alone makes it likely that low-lying areas where tens of millions of people live will become uninhabitable by the end of this century. Entire island nations are at risk. Then it will get worse. Even if humanity controls greenhouse emissions enough to halt further global warming, the gases already in the air will capture heat energy that will work its way gradually deeper into the oceans. The tides will continue to creep higher, century after century. Meanwhile, if the planet warms up a few degrees (which is the most likely scenario unless strong restrictions on emissions are promptly introduced), the forces melting polar ice will become irreversible. Eventually, probably after several thousand years, the Greenland Ice Sheet will be gone. Even if nothing happens in Antarctica, that will put the sea level seven meters higher, giving posterity its grandest, but unwelcome, monument of our civilization.[2]

*See the separate essay on expected impacts of global warming.*

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[1] Webster et al. (2005), published Sept. 16, found in all ocean basins "a large increase... in the number and proportion of hurricanes reaching categories 4 and 5." Also influential was a computer study, Knutson and Tuleya (2004), and a leading expert's insistance, in response to the violent 2004 storm season, that "hurricanes are changing," Trenberth (2005). See also, among others, Hoyos et al. (2006); Wu et al. (2006). Summary of models: Meehl et al. (2007), pp. 786-88. For the controversy: Pearce (2005b); Kunzig (2006); Witze (2006); Valerie Bauerlein, "Hurricane Debate Shatters Civility of Weather Science," *Wall Street Journal,* Feb. 2, 2006, p. 1; Emanuel (2005b); Mooney (2007a). "Remain a point of debate:" Kossin et al. (2007).

[2] Commitment to sea level change is summarized in Meehl et al. (2007), p. 752.