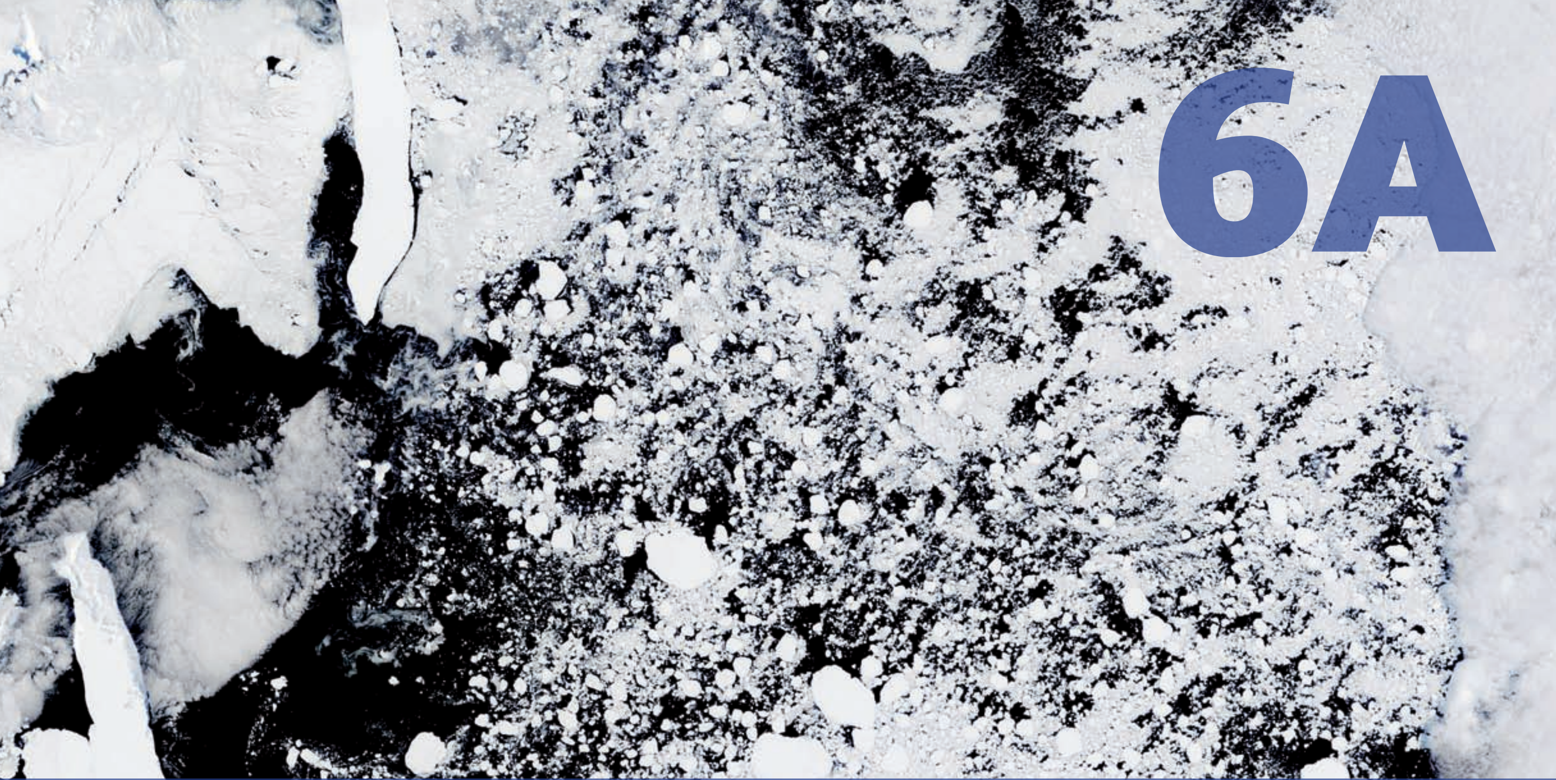

6A

Ice Sheets

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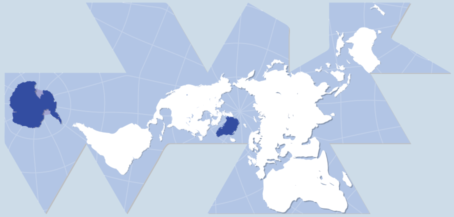
Ice Sheets

Ice sheet: a mass of land ice, continental or sub-continental in extent, and thick enough to cover most of the underlying bedrock topography. Its shape is mainly determined by the dynamics of its outward flow. There are only two ice sheets in the modern world, on Greenland and Antarctica; during glacial periods there were others.



Ice shelf: a thick, floating slab of freshwater ice extending from the coast (originating as land ice). Nearly all ice shelves are in Antarctica.

	Area Covered (million square km)	Ice Volume (million cubic km)	Potential Sea Level Rise (cm)
Ice sheets (total)	**14.0**	**27.6**	**6390**
Greenland	1.7	2.9	730
Antarctica	12.3	24.7	5660
Ice shelves	**1.5**	**0.7**	**0**

Source: IPCC 2007[35]

Summary

The vast polar ice sheets are shrinking as our climate becomes warmer. Floating ice shelves and glacier tongues are thinning and even breaking up in both Greenland and Antarctica, probably because of the combined effects of warming ocean waters and increasing summer air temperatures. Much of this floating ice fills coastal embayments, and is pushed seawards by tributary glaciers, which are observed to accelerate, as much as eightfold, following ice-shelf break-up. At the same time, warmer summers are extending the zone and intensity of summer melting to higher elevations, particularly in Greenland. This increases both meltwater runoff into the ocean and meltwater drainage to the bed, where it lubricates glacier sliding and potentially increases ice discharge into the ocean.

Together these changes have resulted in net losses from both ice sheets at rates that are increasing with time. Corresponding sea-level rise increased from about 0.2 mm per year in the early 1990s to perhaps 0.8 mm per year since 2003, contributing to the total observed rise during the 1990s of approximately 3 mm per year. Some of the thinning glaciers extend many tens to hundreds of kilometres inland, and whether or not ice losses continue to accelerate will depend partly on whether ice shelves continue to thin, and partly on how far inland the zones of glacier acceleration can extend. These questions represent a major challenge to scientists, and their answers could have a profound impact on all of us. Research planned for the International Polar Year in 2007-2008 aims to answer them.

Introduction to the ice sheets

Greenland and Antarctica contain 98–99 per cent of the freshwater ice on Earth's surface. Buried layers of ice, formed from annual snowfall, preserve records of past

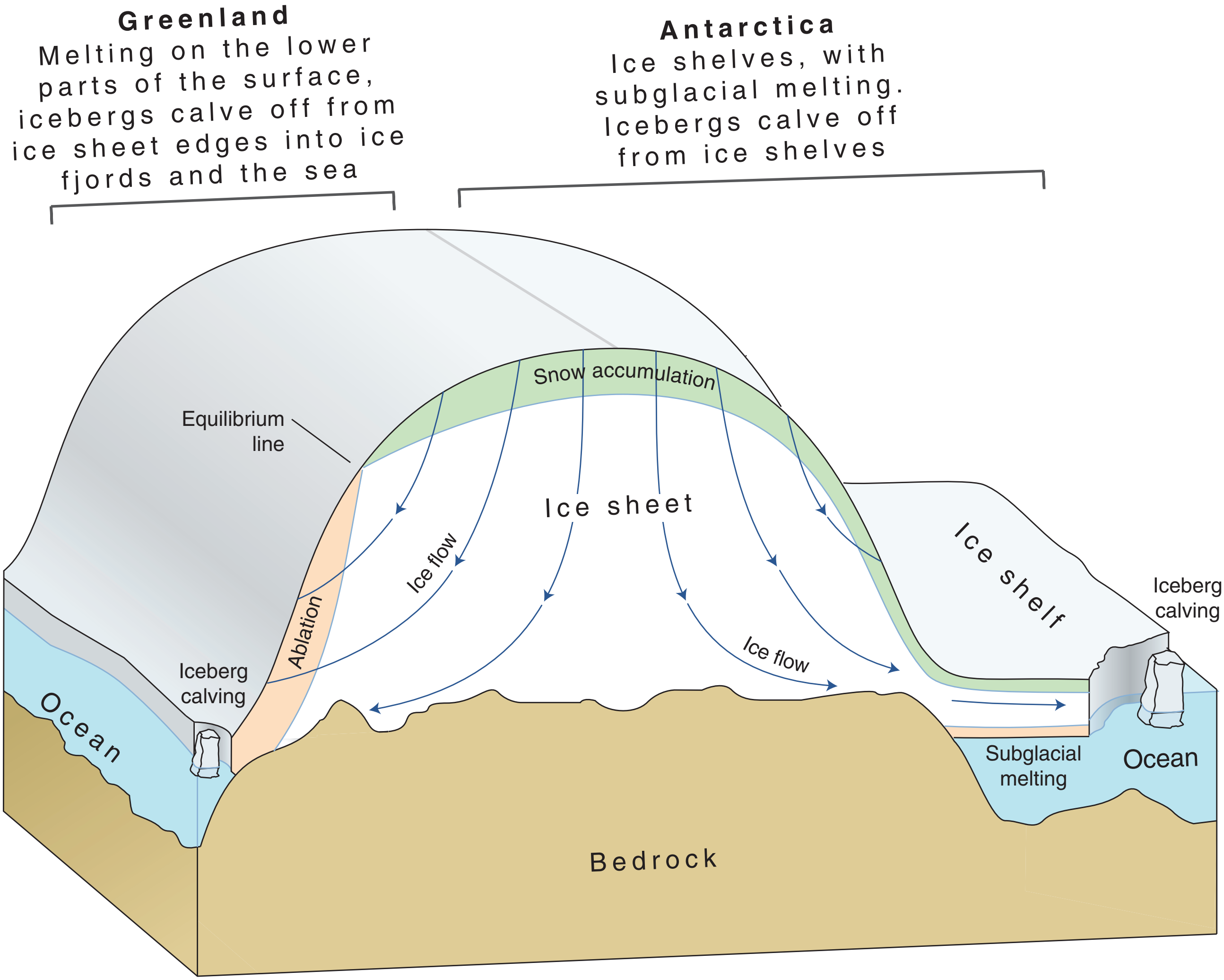


Figure 6A.1: Ice sheets.

Source: based on material provided by K. Steffen, CIRES/Univ. of Colorado

climate and air composition dating back hundreds of millennia. During glacial periods, ice sheets contained more than twice as much ice as that in Greenland and Antarctica today. Sea level would rise by about 64 m if the current mass of ice in Greenland and Antarctica were to melt completely. Although this would take many thousands of years, recent observations show a marked increase in ice-sheet contributions to sea-level rise. In addition, ice-sheet melting strongly influences ocean salinity and temperature, and also global thermohaline circulation as a consequence (see Chapter 2). Since variations in sea surface temperature also influence fluxes of heat and fresh water to the atmosphere, this forms a feedback mechanism – changes to the ocean caused by meltwater from ice sheets directly influence how much snow builds up on the ice sheets themselves. Ice sheets are thus an active and important part of an interconnected climate system.

The ice cover in Greenland and Antarctica has two components (Figure 6A.1) – thick, grounded, inland ice that rests on a more or less solid bed, and thinner floating ice shelves and glacier tongues. An ice sheet is actually a giant glacier, and like most glaciers it is nourished by the continual accumulation of snow on its surface. As successive layers of snow build up, the layers beneath are gradually compressed into solid ice. Snow input is balanced by glacial outflow, so the height of the ice sheet stays approximately constant through time. The ice is driven by gravity to slide and to flow downhill from the highest points of the interior to the coast. There it either melts or is carried away as icebergs which also eventually melt, thus returning the water to the ocean whence it came.

Outflow from the inland ice is organized into a series of drainage basins separated by ice divides that concentrate the flow of ice into either narrow mountain-bounded outlet glaciers or fast-moving ice streams surrounded by slow-moving ice rather than rock walls. In Antarctica much of this flowing ice has reached the coast and has spread over the surface of the ocean to form ice shelves that are floating on the sea but are attached to ice on land. There are ice shelves along more than half of Antarctica's coast, but very few in Greenland.

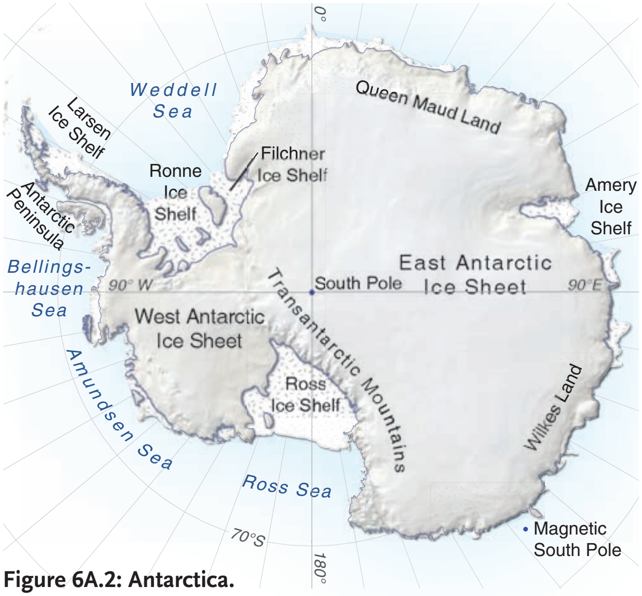


Figure 6A.2: Antarctica.

Antarctica

Antarctic inland ice ranges in thickness up to 5000 m, with an average thickness of about 2400 m, making Antarctica by far the highest of the continents. Straddling the South Pole, Antarctica is cold even during summer. Much of the continent is a cold desert with very low precipitation rates. Thus, in contrast to Greenland, only a tiny proportion of the mass loss from the Antarctic Ice Sheet occurs by melting from the surface – summertime melt from the margins of the ice sheet only occurs in the northern Antarctic Peninsula and the northernmost fringes of East Antarctica. Instead, most ice loss from Antarctica is from basal melting and iceberg calving from the vast floating ice shelves.

The West Antarctica Ice Sheet (WAIS) drains mostly into the Ross Ice Shelf, at the head of the Ross Sea; but also into the Filchner/Ronne Ice Shelf (two connected ice shelves), at the head of the Weddell Sea; and into small ice shelves along the Amundsen Sea coast. The Ross and Filchner/Ronne ice shelves are each about the area of Spain (see Figure 6A.2).

Glaciological interest is concentrated particularly on the WAIS because it rests on a bed far below sea level, which may make it particularly vulnerable to accelerated discharge into the ocean. If the entire WAIS were to disappear, sea level would rise by 5 or 6 meters, with major consequences (see Section 6C).

The WAIS was significantly larger during the last glacial maximum, 20 000 years ago, and retreated to near its present extent within the last several thousand years and it is probably still retreating today[1]. Several postglacial mechanisms, notably isostatic uplift (a slow rise in the level of the land) and the penetration of ice-softening warmth into the deeper layers, have long response times. The ice sheet is still reacting dynamically to the glacial-interglacial transition and to the postglacial increase in the rate of snowfall[2]. Consequently, the present Antarctic contribution to sea-level change probably reflects a long-term dynamic response of the ice sheet as well as changes in the atmospheric and oceanic climate over the last century.

Greenland

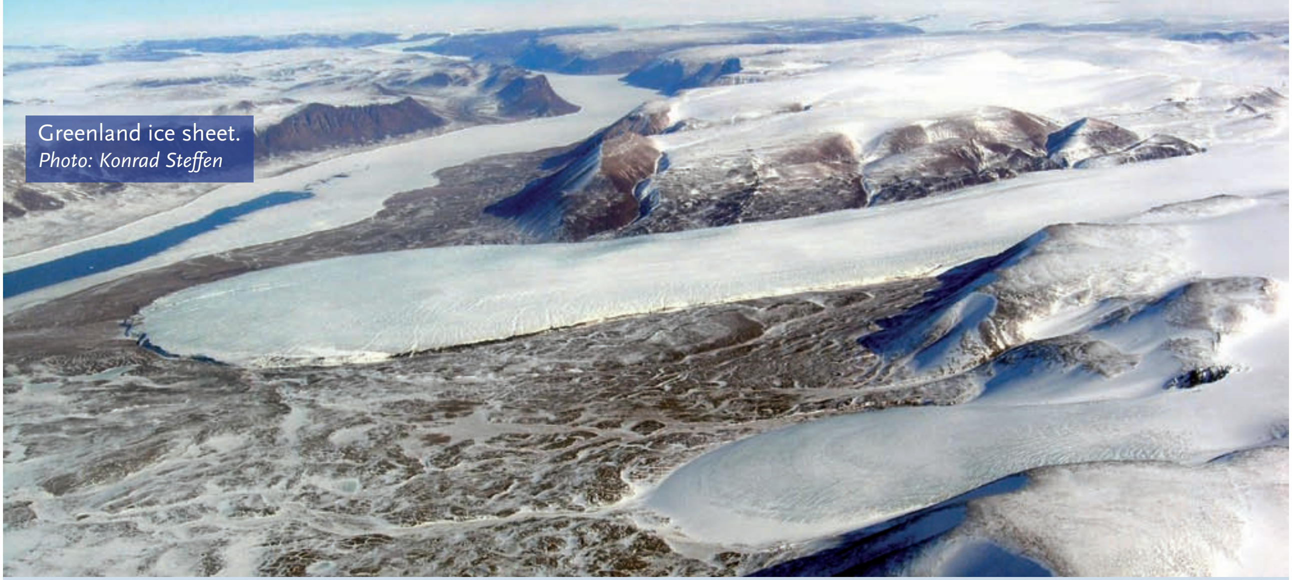
The Greenland Ice Sheet extends from 60° to 80° N, and covers an area of 1.7 million square km. With an average thickness of 1600 m, it has a total volume of about 3 million cubic km (about one ninth of the volume of the Antarctic Ice Sheet) – roughly equivalent to a sea-level rise of 7 m. It comprises a northern dome and a southern dome, with maximum surface elevations of approximately 3200 m and 2850 m respectively, linked by a long saddle with elevations around 2500 m. Bedrock beneath the central part of the ice sheet is remarkably flat and close to sea level, but the ice sheet is fringed almost completely by coastal mountains through which it is drained by many glaciers.

Greenland's climate is strongly affected by its proximity to other land masses and to the North Atlantic, leading to a proportionately higher rate of exchange of water between ice sheet and ocean than in Antarctica. Summer melting occurs over about half of the ice-sheet surface, with much of the meltwater flowing into the sea, either along channels cut into the ice surface or by draining to the bed via crevasses. The average snow accumulation rate is more than double that of Antarctica. There are only a few ice shelves and, where they do exist, basal melting rates are much higher than in Antarctica – they can exceed 10 m per year. This gives an indication of the potential effect warmer Southern Ocean temperatures would have on Antarctic ice shelves.

The Greenland Ice Sheet is particularly important to the study of sea-level change in a warming climate for two reasons. First, it is likely to respond rapidly to warmer temperatures because surface melting already occurs widely. This means that small increases in air temperatures result in large inland migrations of summer melt zones up the gentle slopes of interior parts of the ice sheet. Increasing summer melt reduces ice-sheet volume directly, by drainage into the ocean, and indirectly, by lubricating the base of outlet glaciers and increasing their total ice discharge into the ocean. Second, Greenland provides a picture of Antarctic conditions if climate warms enough to weaken or remove key ice shelves. Recent observations in Antarctica confirm the early predictions of substantial glacier acceleration following ice-shelf removal.

Recent mass balance analyses

Until recently, it was not possible to determine whether the polar ice sheets were growing or shrinking. Over the last decade, improved remote-sensing techniques combined with accurate GPS positioning have made it possible to estimate ice-sheet mass balance (see box on how to tell if an ice sheet is growing or shrinking).



How to tell if an ice sheet is growing or shrinking

The mass balance of an ice sheet, meaning the rate of change of its mass, is vitally important because changes in mass balance are transformed directly into global sea-level change. Measurement is difficult and a range of techniques has to be used to get an overall picture of change in the ice sheets. There are two basic approaches – the integrated approach and the component approach.

The integrated approach involves measuring changes in the surface height (hence volume) or gravitational attraction (hence mass) of the ice sheet using instruments mounted in satellites. These instruments include radar and laser altimeters and high-precision gravity-measuring systems. Laser altimeters can detect small surface elevation changes, but are hampered by persistent cloud cover. Satellite surveys began only in 2003. Aircraft laser measurements over Greenland began ten years earlier and, although they provide only limited coverage, flight lines can be along specified routes such as glacier flow lines. Radar altimeters have less precision, suffer errors associated with radar penetration into the ice sheet surface, and give poor results in rough or steep terrain, but their longer history is still a boon for measurements of change. The gravity-based techniques can measure changes in overall mass to an astonishing level of precision, but the accuracy of ice-sheet mass balance estimates is hampered by limited knowledge of how much mass change is caused by uplift of the rock beneath by geologic forces.

The component approach involves comparing the mass added by snowfall on the ice sheet to that lost into the surrounding ocean. Mass input is based on estimates of snow-accumulation rates from counting annual layers in snow pits and ice cores, measuring depths to well-dated radioactive fallout horizons, or weather-model simulations. Newer remote sensing methods are promising but not yet fully developed. Mass output by meltwater runoff is generally estimated from models; to that must be added the solid-ice flux, given by the product of ice flow velocity and thickness at coastal margins. Ice thickness is generally measured by radar sounding from airplanes, and ice velocity is measured by repeated GPS surveys of ice markers, tracking of crevasses and other ice features in high-resolution satellite imagery, and analysis of repeated satellite radar images. This last technique, in particular, has made it possible to measure the speed of ice movement over vast regions at high spatial resolution.

All these techniques for measuring mass balance have significant errors but because they offer independent estimates, they provide an increased level of confidence in their collective conclusions. However, interpretation of mass-balance estimates is further complicated by high natural variability that occurs on a range of time scales. Separation of long-term trends in ice mass from the effects of this variability requires observations over long time periods.

Antarctica (see Figure 6A.3)

Measurements by satellite techniques based on gravity indicate mass loss at a rate of 138 ± 73 billion tonnes per year during 2002–2005, mostly from the WAIS[6]. That is equivalent to a rise in global sea level of 0.4 ± 0.2 mm per year, or 10–30% of the global rate measured since the 1950s (see Chapter 6C), and is in good agreement with recent mass-budget estimates[10]. However, two interpretations of satellite radar altimetry pointed to a much smaller loss of about 31 billion tonnes of ice per year[8] or a net gain of about 27 billion tonnes per year[9]. The difference between these estimates from totally independent techniques reflects the uncertainties in these difficult measurements; nevertheless, on balance, they indicate a recent shift to a net loss of Antarctic ice and suggest that losses may be accelerating. Similar conclusions result from studies of Antarctic Peninsula glaciers, indicating that they are melting much faster than previously predicted and are probably already contributing significantly to sea-level rise[11].

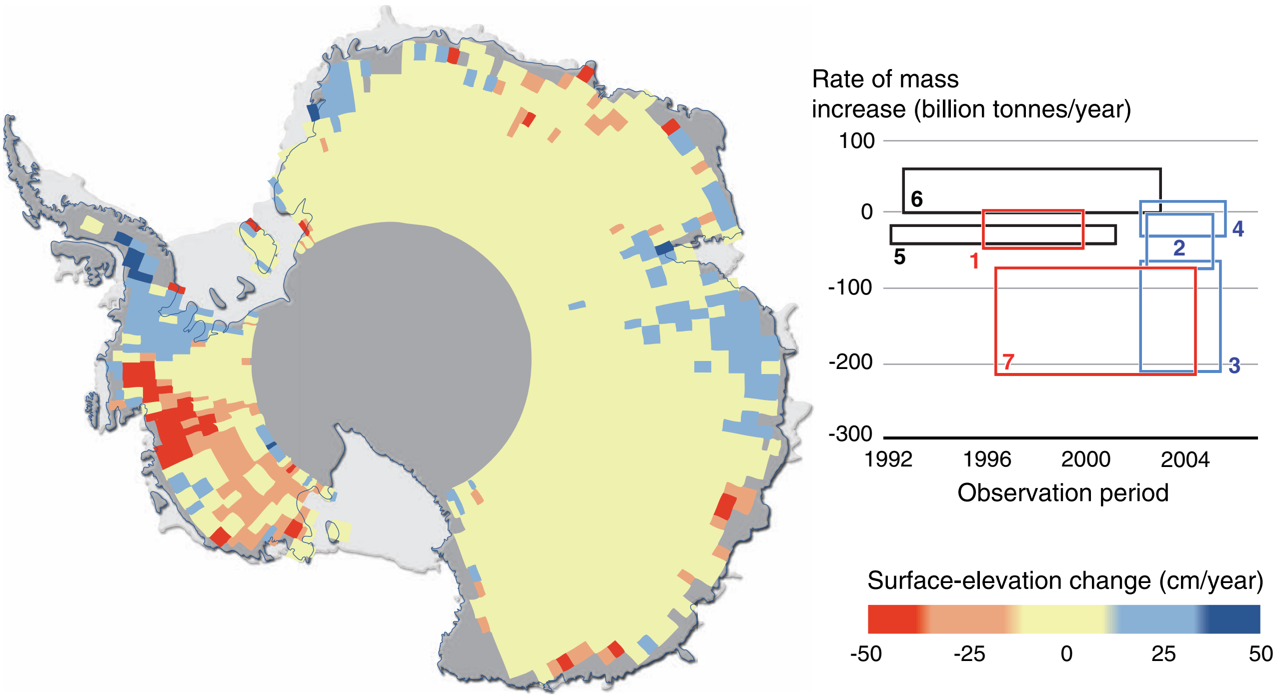


Figure 6A.3: Antarctica, showing rates of surface-elevation change derived from satellite radar-altimeter measurements[3]. The graph shows rates at which the ice-sheet mass was estimated to be changing based on radar-altimeter data (black), mass-budget calculations (red), and satellite gravity measurements (blue). Rectangles depict the time periods of observations (horizontal) and the upper and lower estimates of mass balance (vertical).

Sources (corresponding to numbers on rectangles): 1 Rignot and Thomas 2002[4]; 2 Ramillien and others 2006[5]; 3 Velicogna and Wahr 2006a[6]; 4 Chen and others 2006a[7]; 5 Zwally and others 2005[8]; 6 Wingham and others 2006a[9]; 7 Rignot and others 2007[10]

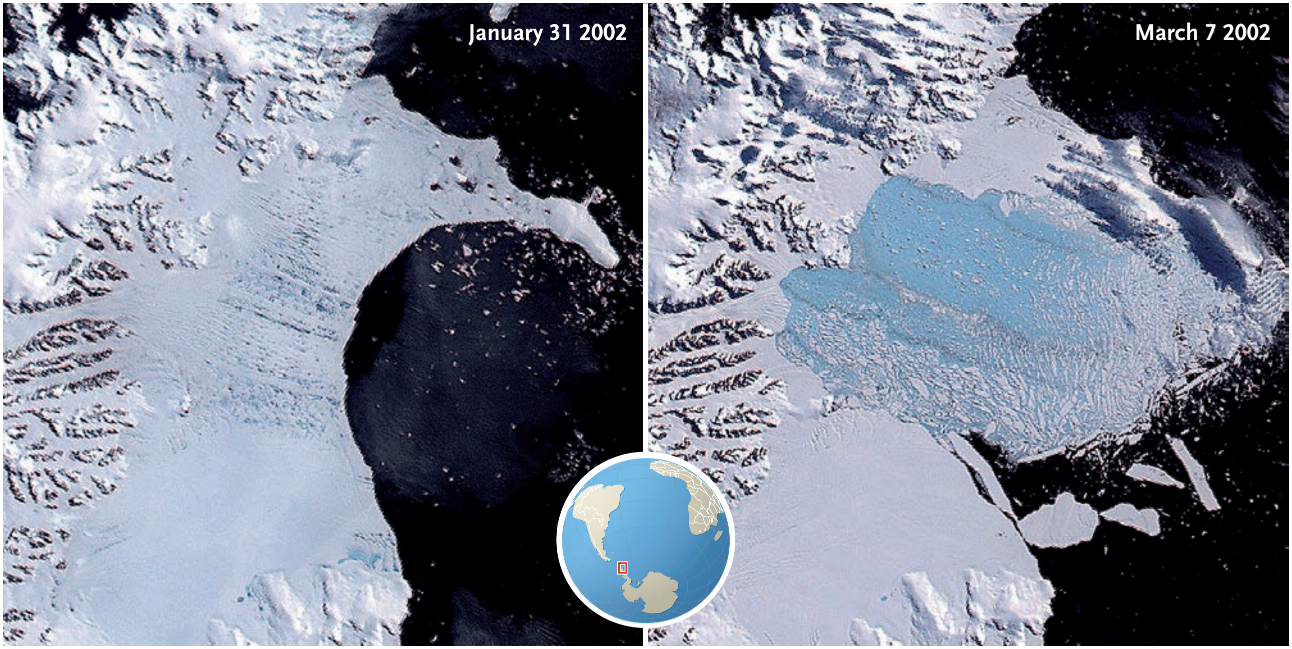


Figure 6A.4: Break-up of the Larsen B ice shelf. These are images from NASA's MODIS satellite sensor. Part of the Antarctic Peninsula is on the left. The image on the left shows the shelf in late summer, with dark bluish melt ponds on the surface. The image on the right, collected only five weeks later, shows a large part of the ice shelf collapsed, with thousands of sliver icebergs at the margins and a large blue area of ice fragments.

Images: National Snow and Ice Data Center

The questionable stability of Antarctic ice shelves in a warming climate was highlighted by the collapse of the Larsen B Ice Shelf in 2002 off the northern Antarctic Peninsula (Figure 6A.4). The significance of this event was highlighted by records from six marine sediment cores in the vicinity showing that this scale of collapse is unprecedented since the end of the last ice age. Research implies that the long-term thinning of the ice shelf has combined with the modern half-century-long warming in the Antarctic Peninsula region to cause its disintegration[12]. Moreover, nine other small ice shelves around the Antarctic Peninsula have broken up over the last 100 years.

The Larsen B collapse prompted researchers to look at the implications of ice-shelf decay for the stability of Antarctica's inland ice. Glaciers that fed the former ice shelf have speeded up by factors of two to eight following the collapse[13]. In contrast, glaciers further south did not accelerate as they are still blocked by an ice shelf. The large magnitude of the glacier changes illustrates the important influence of ice shelves on ice sheet mass balance.

Much further south, in the Amundsen Sea sector of West Antarctica, satellite radar measurements show that ice shelves have thinned by up to 5.5 meters per year over the past decade[14]. The thinning of the ice shelves, apparently from ocean currents that are on average 0.5°C warmer than freezing, is mirrored by the thinning and acceleration of their tributary glaciers[15,16]. These accelerating glaciers drain a region widely believed to be the most vulnerable portion of the WAIS because its bed is so deep below sea level. Collapse of the entire region into the sea would raise sea level by about 1 m.

Elsewhere, recent detailed high-resolution satellite imagery charted the simultaneous rise and compensating fall of a score of patches on the Antarctic Ice Sheet, reflecting extensive water movement under the ice and pointing to the potentially destabilizing effect of subglacial water[17–19]. Although the volumes of water are tiny in terms of sea-level change, the observations reveal a widespread, dynamic subglacial water system, which may exert an important control on ice flow, and hence on the mass balance of the entire ice sheet.

Greenland (see Figure 6A.5)

Mass-balance estimates for Greenland show thickening at high elevations since the early 1990s at rates that increased to about 4 cm per year after 2000, consistent with expectations of increasing snowfall in a warming climate. However, this mass gain is far exceeded by losses associated with large increases in thinning of the ice sheet near the coast.

Total loss from the ice sheet more than doubled, from a few tens of billions of tonnes per year in the early 1990s[20], to about 100 billion tonnes per year after 2000[27], with perhaps a further doubling by 2005[24]. These rapidly increasing losses result partly from more melting during warmer summers, and partly from increased discharge of ice from outlet glaciers into the ocean[22]. In particular, the speeds of three of Greenland's fastest glaciers approximately doubled since 2000[28,29], although two of them have partially slowed since[30]. The third glacier, Jakobshavn Isbrae (Figure 6A.6), increased its speed to about 14 km per year[28] after rapid thinning and break up of its floating ice tongue[31], without any signs of slowing down. The bed is very deep for several tens of kilometres inland, allowing seaward parts of the glacier to float and break up as the ice thins. By contrast, nearby glaciers with shallow beds have only small thinning rates, indicating a strong linkage between bed topography and glacier vulnerability to change.

In addition, marked increases in ice velocity occurring soon after periods of heavy surface melting suggest that meltwater draining to the base of the ice lubricates glacier sliding[32] (Figure 6A.7). This indicates that increased melting in a warmer climate could cause an almost simultaneous increase in ice-discharge rates.

Outlook for the ice sheets

For many reasons, it is not possible now to predict the future of the ice sheets, in either the short or long term, with any confidence[33]. Modeling ice sheet dynamic behaviour is seriously hampered by a paucity of observational data about the crucial, controlling conditions at the ice-sheet bed[2,34]. It is because of these uncertainties that the projections of the IPCC 4th Assessment Report, while including contributions from Greenland and Antarctica at the increased rates observed for 1993–2003, state that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise"[35].

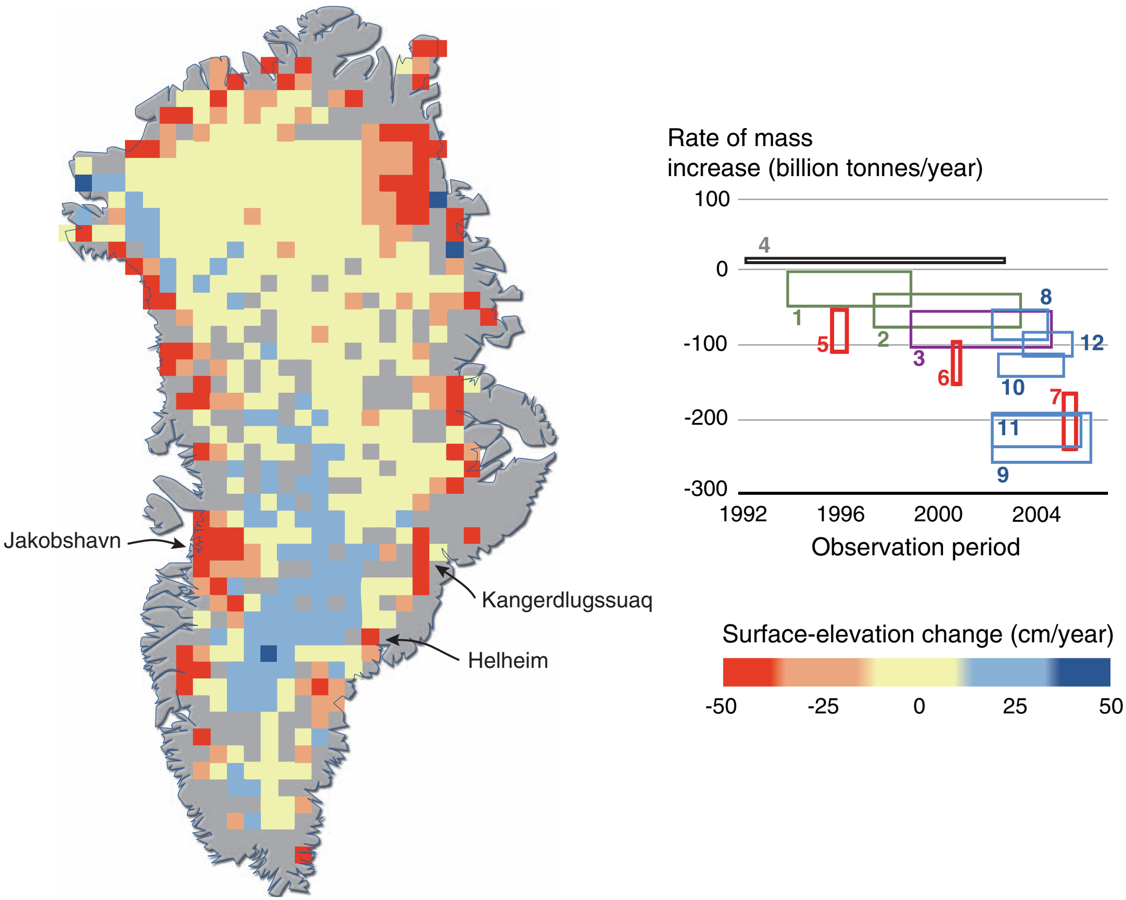
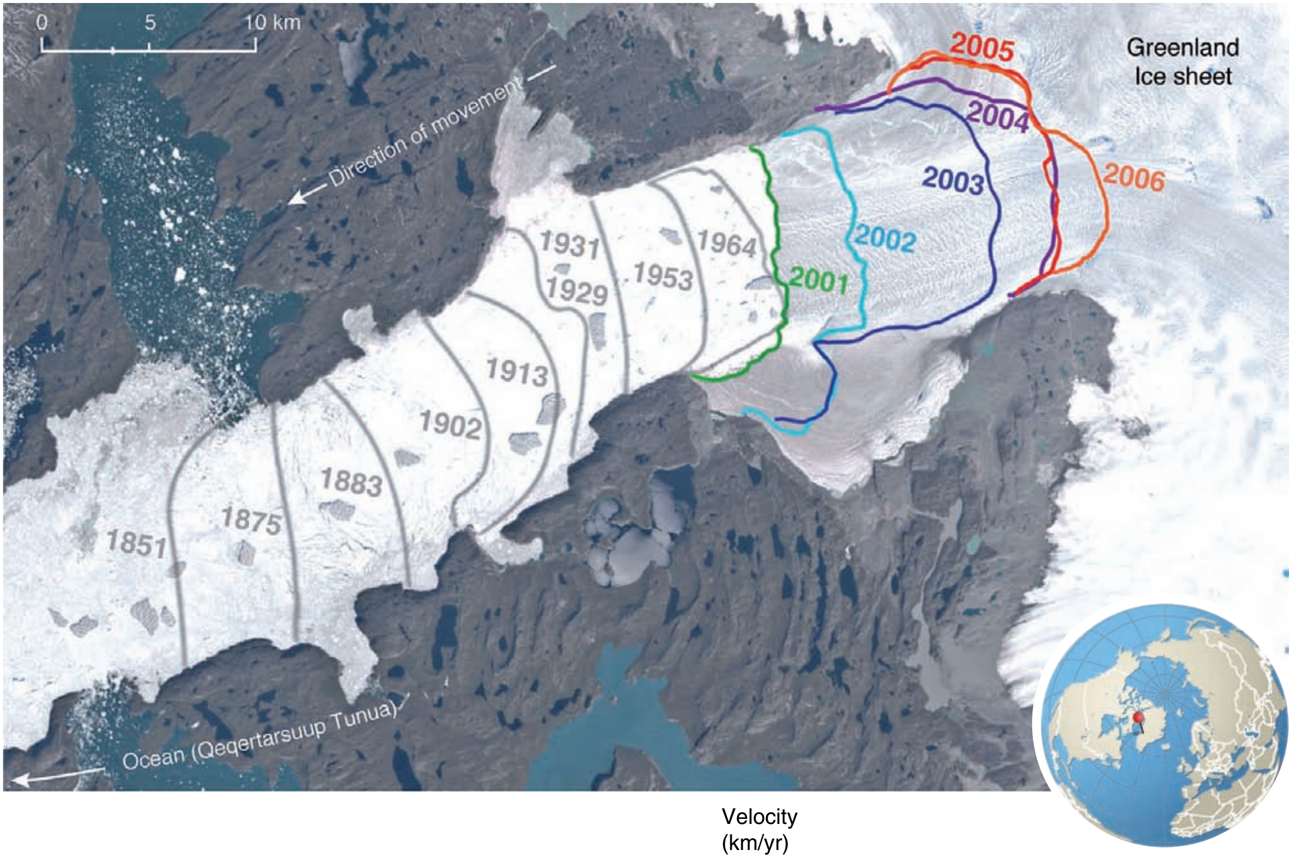


Figure 6A.5: Greenland, showing rates of surface-elevation change between the late 1990s and 2003, derived by comparing satellite and aircraft laser-altimeter surveys. The graph shows rates at which the ice-sheet mass was estimated to be changing based on satellite radar-altimeter surveys (black), airborne laser-altimeter surveys (green), airborne/satellite laser-altimeter surveys (purple), mass-budget calculations (red), temporal changes in gravity (blue). Rectangles depict the time periods of observations (horizontal) and the upper and lower estimates of mass balance (vertical). Jakobshavn, Helheim, and Kangerdlugssuaq are fast glaciers that doubled in speed recently.

Sources (corresponding to numbers on rectangles): 1 and 2 Krabill and others 2000[20] and 2004[21]; 3 Thomas and others 2006[27]; 4 Zwally and others 2005[8]; 5 to 7 Rignot and Kanagaratnam 2006[22]; 8 and 9 Velicogna and Wahr 2005[23] and 2006A[24]; 11 Chen and others 2006A[25]; 10 Ramillien and others 2006[5]; 12 Luthke and others 2006[26]



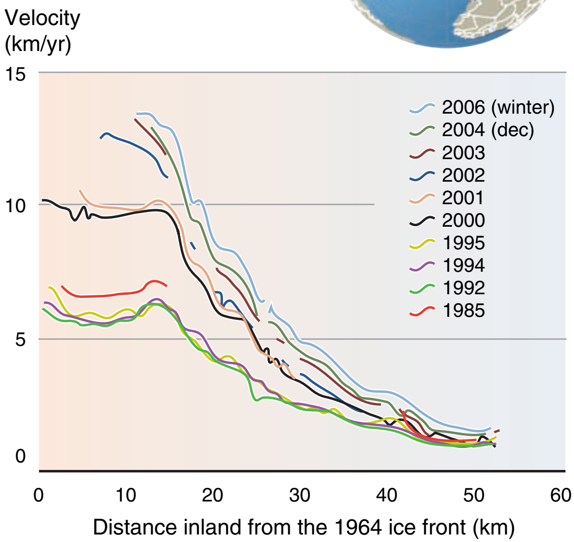


Figure 6A.6: Landsat satellite image of Jakobshavn Isbrae and its fjord, showing locations of the calving ice front in years from 1851 to 2006. The glacier extends through the Illulisat Icefjord, surrounded by mountains. Icebergs calve off from the main glacier, pile up and block the fjord before being released into Qeqertarsuup Tunua (Disko) Bay and Davis Strait. The whiter areas in the fjord are piled-up icebergs and the "real" glacier ends where the greyish striped section ends – showing that this image is from 2001.
The graph shows glacier-velocity profiles for 1985 to 2006. During this period Jakobshavn Isbrae, already the world's fastest glacier, doubled its speed to almost 14 km per year[28,29] after rapid thinning and break up of its floating ice tongue[31].

Sources: NASA/Goddard Space Flight Center Scientific Visualization Studio. Historic calving front locations courtesy of Anker Weidick and Ole Bennike
Source: based on Howatt and others 2007[30]

Figure 6A.7: Surface melting on the Greenland Ice Sheet drains down to the base of the ice sheet and lubricates its flow over the bed rock.
Photo: Roger Braithwaite/Still Pictures

Recent signs point to accelerating loss of ice in both Greenland and Antarctica. It is becoming increasingly apparent that some changes, such as the break up of ice shelves in Antarctica, are exceptional when one looks over periods of centuries to millennia. For the ice sheets of both polar regions, some of these very fast changes are caused not by melting (included in the IPCC predictions), but by changes in glacier dynamics (not fully included in the IPCC predictions).

The slow, measured behaviour long associated with the Greenland Ice Sheet is being transformed to the rapidly changing characteristics more typical of big glaciers in Alaska and Patagonia. A zone of glacier acceleration is progressively moving northward, leaving Greenland's southern ice dome under threat from both increased summer melting near the coasts, and increased ice discharge down glaciers that extend their influence far inland. If this continues, it is quite possible that the ice dome in southern Greenland will reach a tipping point, with accelerating positive feedback causing its ever more rapid decline and an associated sea-level rise of about 85 cm. Moreover, continued northward migration of the zone of glacier acceleration would make the far larger northern dome also vulnerable.

In Antarctica, disintegration of the WAIS continues to be the primary threat. The key issue is whether the main body of the WAIS would accelerate rapidly if its ice shelves were thinned or removed by a warming climate[36,37]. There are clues. Ice-shelf break up along the Antarctic Peninsula has resulted in massive acceleration of tributary glaciers and ice-shelf thinning further south, along the Amundsen Sea, also appears to have caused glacier acceleration. Here, the acceleration is more modest, but the glaciers are far bigger, so total losses are large. No one knows how far inland the zone of glacier acceleration will spread, and no one knows why the ice shelves are breaking up. However, their thinning is almost certainly caused by increased basal melting, implicating the ocean. And final break up seems to be accelerated if there is sufficient surface meltwater to fill, and over-deepen, crevasses in the ice shelves, effectively wedging the ice shelf apart into fragments.

Observations made over the past five years have made it clear that existing ice-sheet models cannot simulate the widespread rapid glacier thinning that is occurring, and ocean models cannot simulate the changes in the ocean that are probably causing some of the dynamic ice thinning. Consequently, in its Fourth Assessment, the IPCC has taken a conservative approach by not attempting to predict the unpredictable. As a result, these projections[35] of future ice-sheet related rises in sea level should be regarded as lower bounds.

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