

### TS.3.2 Changes in the Cryosphere: Instrumental Record

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Currently, ice permanently covers 10% of the land surface, with only a tiny fraction occurring outside Antarctica and Greenland. Ice also covers approximately 7% of the oceans in the annual mean. In midwinter, snow covers approximately 49% of the land surface in the NH. An important property of snow and ice is its high surface albedo. Because up to 90% of the incident solar radiation is reflected by snow and ice surfaces, while only about 10% is reflected by the open ocean or forested lands, changes in snow and ice cover are important feedback mechanisms in climate change. In addition, snow and ice are effective insulators. Seasonally frozen ground is more extensive than snow cover, and its presence is important for energy and moisture fluxes. Therefore, frozen surfaces play important roles in energy and climate processes. {4.1}

The cryosphere stores about 75% of the world's freshwater. At a regional scale, variations in mountain snowpack, glaciers and small ice caps play a crucial role in freshwater availability. Since the change from ice to liquid water occurs at specific temperatures, ice is a component of the climate system that could be subject to abrupt change following sufficient warming. Observations and analyses of changes in ice have expanded and improved since the TAR, including shrinkage of mountain glacier volume, decreases in snow cover, changes in permafrost and frozen ground, reductions in arctic sea ice extent, coastal thinning of the Greenland Ice Sheet exceeding inland thickening from increased snowfall, and reductions in seasonally frozen ground and river and lake ice cover. These allow an improved understanding of how the cryosphere is changing, including its contributions to recent changes in sea level. The periods from 1961 to the present and from 1993 to the present are a focus of this report, due to the availability of directly measured glacier mass balance data and altimetry observations of the ice sheets, respectively. {4.1}

**Snow cover has decreased in most regions, especially in spring.** Northern Hemisphere snow cover observed by satellite over the 1966 to 2005 period decreased in every month except November and December, with a stepwise drop of 5% in the annual mean in the late 1980s (see [Figure TS.12](#)). In the SH, the few long records or proxies mostly show either decreases or no changes in the past 40 years or more. Northern Hemisphere April snow cover extent is strongly correlated with 40°N to 60°N April temperature, reflecting the feedback between snow and temperature. {4.2}

#### CHANGES IN SNOW COVER

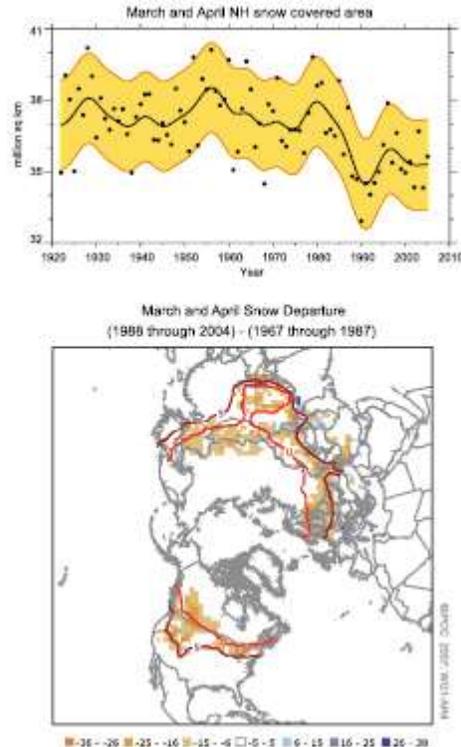


Figure TS.12. (Top) Northern Hemisphere March-April snow-covered area from a station-derived snow cover index (prior to 1972) and from satellite data (during and after 1972). The smooth curve shows decadal variations (see [Appendix 3.A](#)) with the 5 to 95% data range shaded in yellow. (Bottom) Differences in the distribution of March-April snow cover between earlier (1967–1987) and later (1988–2004) portions of the satellite era (expressed in percent coverage). Tan colours show areas where snow cover has declined. Red curves show the 0°C and 5°C isotherms averaged for March-April 1967 to 2004, from the Climatic Research Unit (CRU) gridded land surface temperature version 2 (CRUTEM2v) data. The greatest decline generally tracks the 0°C and 5°C isotherms, reflecting the strong feedback between snow and temperature. {Figures [4.2](#), [4.3](#)}

**Decreases in snowpack have been documented in several regions worldwide based upon annual time series of mountain snow water equivalent and snow depth.** Mountain snow can be sensitive to small changes in temperature, particularly in temperate climatic zones where the transition from rain to snow is generally closely associated with the altitude of the freezing level. Declines in mountain snowpack in western North America and in the Swiss Alps are largest at lower, warmer elevations. Mountain snow water equivalent has declined since 1950 at 75% of the stations monitored in western North America. Mountain snow depth has also declined in the Alps and in southeastern Australia. Direct observations of snow depth are too limited to determine changes in the Andes, but temperature measurements suggest that the altitude where snow occurs (above the snow line) has probably risen in mountainous regions of South America. {[4.2](#)}

**Permafrost and seasonally frozen ground in most regions display large changes in recent decades.** Changes in permafrost conditions can affect river runoff, water supply, carbon exchange and landscape stability, and can cause damage to infrastructure. Temperature increases at the top of the permafrost layer of up to 3°C since the 1980s have been reported. Permafrost warming has also been observed with variable magnitude in the Canadian Arctic, Siberia, the Tibetan Plateau and Europe. The permafrost base is thawing at a rate ranging from 0.04 m yr<sup>-1</sup> in Alaska to 0.02 m yr<sup>-1</sup> on the Tibetan Plateau. {[4.7](#)}

**The maximum area covered by seasonally frozen ground decreased by about 7% in the NH over the latter half of the 20th century, with a decrease in spring of up to 15%.** Its maximum depth has decreased by about 0.3 m in Eurasia since the mid-20th century. In addition, maximum seasonal thaw depth increased by about 0.2 m in the Russian Arctic from 1956 to 1990. {[4.7](#)}

On average, the general trend in NH river and lake ice over the past 150 years indicates that the freeze-up date has become later at an average rate of  $5.8 \pm 1.9$  days per century, while the breakup date has occurred earlier, at a rate of  $6.5 \pm 1.4$  days per century. However, considerable spatial variability has also been observed, with some regions showing trends of opposite sign. {4.3}

Annual average arctic sea ice extent has shrunk by about  $2.7 \pm 0.6\%$  per decade since 1978 based upon satellite observations (see Figure TS.13). The decline in summer extent is larger than in winter extent, with the summer minimum declining at a rate of about  $7.4 \pm 2.4\%$  per decade. Other data indicate that the summer decline began around 1970. Similar observations in the Antarctic reveal larger interannual variability but no consistent trends during the period of satellite observations. In contrast to changes in continental ice such as ice sheets and glaciers, changes in sea ice do not directly contribute to sea level change (because this ice is already floating), but can contribute to salinity changes through input of freshwater. {4.4}

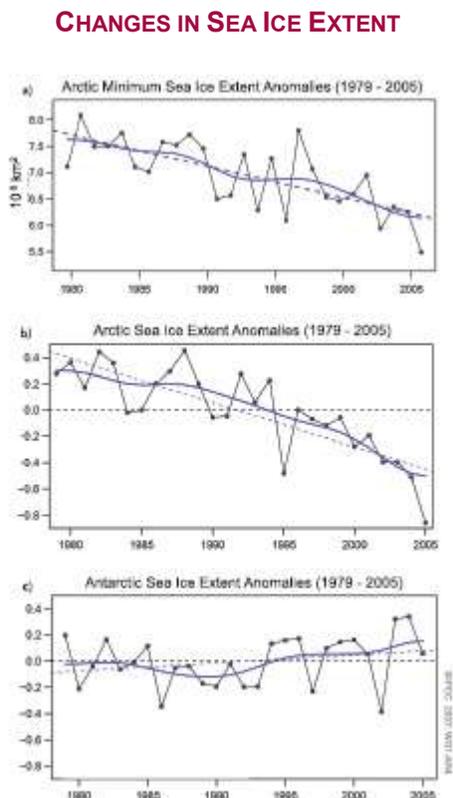


Figure TS.13. (a) Arctic minimum sea ice extent; (b) arctic sea ice extent anomalies; and (c) antarctic sea ice extent anomalies all for the period 1979 to 2005. Symbols indicate annual values while the smooth blue curves show decadal variations (see Appendix 3.A). The dashed lines indicate the linear trends. (a) Results show a linear trend of  $-60 \pm 20 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ , or approximately  $-7.4\%$  per decade. (b) The linear trend is  $-33 \pm 7.4 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$  (equivalent to approximately  $-2.7\%$  per decade) and is significant at the 95% confidence level. (c) Antarctic results show a small positive trend of  $5.6 \pm 9.2 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ , which is not statistically significant. {Figures 4.8 and 4.9}

During the 20th century, glaciers and ice caps have experienced widespread mass losses and have contributed to sea level rise. Mass loss of glaciers and ice caps (excluding those around the ice sheets of Greenland and Antarctica) is estimated to be  $0.50 \pm 0.18 \text{ mm yr}^{-1}$  in sea level equivalent (SLE) between 1961 and 2003, and  $0.77 \pm 0.22 \text{ mm yr}^{-1}$  SLE between 1991 and 2003. The late 20th-century glacier wastage likely has been a response to post-1970 warming. {4.5}

Recent observations show evidence for rapid changes in ice flow in some regions, contributing to sea level rise and suggesting that the dynamics of ice motion may be a key factor in future responses of ice shelves, coastal glaciers and ice sheets to climate change. Thinning or loss of ice shelves in some near-coastal regions of Greenland, the Antarctic Peninsula and West Antarctica has been associated with accelerated flow of nearby glaciers and ice streams, suggesting that ice shelves (including short ice shelves of kilometres or tens of kilometres in length)

could play a larger role in stabilising or restraining ice motion than previously thought. Both oceanic and atmospheric temperatures appear to contribute to the observed changes. Large summer warming in the Antarctic Peninsula region *very likely* played a role in the subsequent rapid breakup of the Larsen B Ice Shelf in 2002 by increasing summer melt water, which drained into crevasses and wedged them open. Models do not accurately capture all of the physical processes that appear to be involved in observed iceberg calving (as in the breakup of Larsen B). {4.6}

**The Greenland and Antarctic Ice Sheets taken together have *very likely* contributed to the sea level rise of the past decade. It is *very likely* that the Greenland Ice Sheet shrunk from 1993 to 2003, with thickening in central regions more than offset by increased melting in coastal regions. Whether the ice sheets have been growing or shrinking over time scales of longer than a decade is not well established from observations.**

Lack of agreement between techniques and the small number of estimates preclude assignment of best estimates or statistically rigorous error bounds for changes in ice sheet mass balances. However, acceleration of outlet glaciers drains ice from the interior and has been observed in both ice sheets (see Figure TS.14). Assessment of the data and techniques suggests a mass balance for the Greenland Ice Sheet of  $-50$  to  $-100$  Gt yr<sup>-1</sup> (shrinkage contributing to raising global sea level by 0.14 to 0.28 mm yr<sup>-1</sup>) during 1993 to 2003, with even larger losses in 2005. There are greater uncertainties for earlier time periods and for Antarctica. The estimated range in mass balance for the Greenland Ice Sheet over the period 1961 to 2003 is between growth of 25 Gt yr<sup>-1</sup> and shrinkage by 60 Gt yr<sup>-1</sup> ( $-0.07$  to  $+0.17$  mm yr<sup>-1</sup> SLE). Assessment of all the data yields an estimate for the overall Antarctic Ice Sheet mass balance ranging from growth of 100 Gt yr<sup>-1</sup> to shrinkage of 200 Gt yr<sup>-1</sup> ( $-0.27$  to  $+0.56$  mm yr<sup>-1</sup> SLE) from 1961 to 2003, and from  $+50$  to  $-200$  Gt yr<sup>-1</sup> ( $-0.14$  to  $+0.55$  mm yr<sup>-1</sup> SLE) from 1993 to 2003. The recent changes in ice flow are *likely* to be sufficient to explain much or all of the estimated antarctic mass imbalance, with recent changes in ice flow, snowfall and melt water runoff sufficient to explain the mass imbalance of Greenland. {4.6, 4.8}

### Box TS.3: Ice Sheet Dynamics and Stability

Ice sheets are thick, broad masses of ice formed mainly from compaction of snow. They spread under their own weight, transferring mass towards their margins where it is lost primarily by runoff of surface melt water or by calving of icebergs into marginal seas or lakes. Ice sheets flow by deformation within the ice or melt water-lubricated sliding over materials beneath. Rapid basal motion requires that the basal temperature be raised to the melting point by heat from the Earth's interior, delivered by melt water transport, or from the 'friction' of ice motion. Sliding velocities under a given gravitational stress can differ by several orders of magnitude, depending on the presence or absence of deformable sediment, the roughness of the substrate and the supply and distribution of water. Basal conditions are generally poorly characterised, introducing important uncertainties to the understanding of ice sheet stability. {4.6}

Ice flow is often channelled into fast-moving ice streams (that flow between slower-moving ice walls) or outlet glaciers (with rock walls). Enhanced flow in ice streams arises either from higher gravitational stress linked to thicker ice in bedrock troughs, or from increased basal lubrication. {4.6}

Ice discharged across the coast often remains attached to the ice sheet to become a floating ice shelf. An ice shelf moves forward, spreading and thinning under its own weight, and fed by snowfall on its surface and ice input from the ice sheet. Friction at ice shelf sides and over local shoals slows the flow of the ice shelf and thus the discharge from the ice sheet. An ice shelf loses mass by calving icebergs from the front and by basal melting into the ocean cavity beneath. Studies suggest an ocean warming of 1°C could increase ice shelf basal melt by 10 m yr<sup>-1</sup>, but inadequate knowledge of the largely inaccessible ice shelf cavities restricts the accuracy of such estimates. {4.6}

The palaeo-record of previous ice ages indicates that ice sheets shrink in response to warming and grow in response to cooling, and that shrinkage can be far faster than growth. The volumes of the Greenland and Antarctic Ice Sheets are equivalent to approximately 7 m and 57 m of sea level rise, respectively. Palaeoclimatic data indicate that substantial melting of one or both ice sheets has likely occurred in the past. However, ice core data show that neither ice sheet was completely removed during warm periods of at least the past million years. Ice sheets can respond to environmental forcing over very long time scales, implying that commitments to future changes may result from current warming. For example, a surface warming may take more than 10,000 years to penetrate to the bed and change temperatures there. Ice velocity over most of an ice sheet changes slowly in response to changes in the ice sheet shape or surface temperature, but large velocity changes may occur rapidly in ice streams and outlet glaciers in response to changing basal conditions, penetration of surface melt water to the bed or changes in the ice shelves into which they flow. {4.6, 6.4}

Models currently configured for long integrations remain most reliable in their treatment of surface accumulation and ablation, as for the TAR, but do not include full treatments of ice dynamics; thus, analyses of past changes or future projections using such models may underestimate ice flow contributions to sea level rise, but the magnitude of such an effect is unknown. {8.2}

## RATES OF OBSERVED SURFACE ELEVATION CHANGE

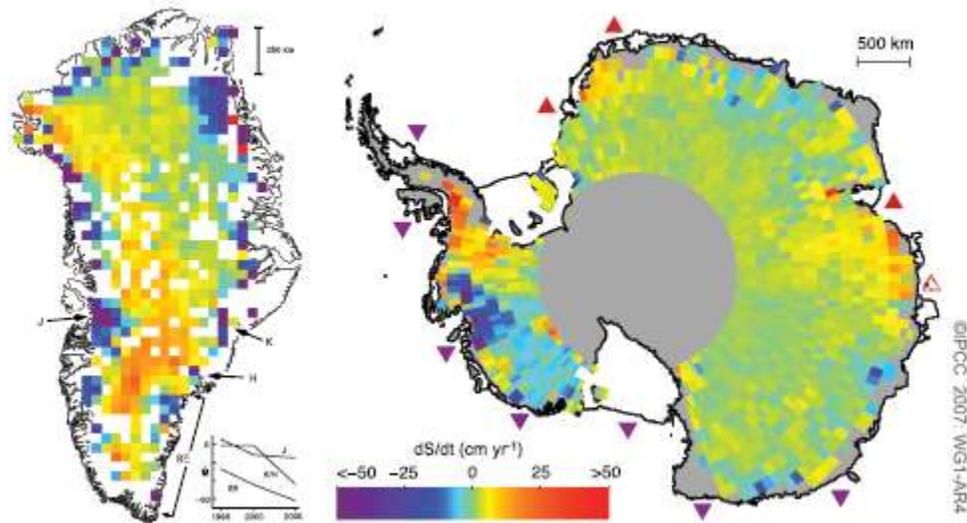


Figure TS.14. Rates of observed recent surface elevation change for Greenland (left; 1989–2005) and Antarctica (right; 1992–2005). Red hues indicate a rising surface and blue hues a falling surface, which typically indicate an increase or loss in ice mass at a site, although changes over time in bedrock elevation and in near-surface density can be important. For Greenland, the rapidly thinning outlet glaciers Jakobshavn (J), Kangerdlugssuaq (K), Helheim (H) and areas along the southeast coast (SE) are shown, together with their estimated mass balance vs. time (with K and H combined, in  $\text{Gt yr}^{-1}$ , with negative values indicating loss of mass from the ice sheet to the ocean). For Antarctica, ice shelves estimated to be thickening or thinning by more than  $30 \text{ cm yr}^{-1}$  are shown by point-down purple triangles (thinning) and point-up red triangles (thickening) plotted just seaward of the relevant ice shelves. {Figures 4.17 and 4.19}