Changes of the Polar Ice Sheets

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***Abstract:** An overview is given of the basic response mechanisms of the Greenland and Antarctic ice sheets to global warming. It is explained how surface mass-balance changes are likely to dominate the response, though it is stressed that important uncertainties remain concerning the present evolution of the ice sheets, the relation between climatic changes and the mass balance terms of snow accumulation and meltwater runoff, and the possible instability of the West Antarctic ice sheet. According to the mid-range of the IPCC (1996) climatic projections, melting would be most important on the Greenland ice sheet and contribute about 10 cm to global sea levels by the year 2100. The Antarctic ice sheet, on the other hand, would grow slightly, because increased precipitation rates would dominate over increased melting rates and dynamic effects in West Antarctica remain small. A likely estimate for the Antarctic contribution to global sea-level lowering is around 10 cm by the year 2100, which would largely balance the Greenland contribution.*

The two great ice sheets that cover Greenland and Antarctica contain over 99% of the global ice volume, and over 90% of the Earth's fresh water resources. Although these ice sheets lie in remote areas, where their behaviour poses little immediate hazard to human activities, they do have a crucial impact on the global environment. This is, amongst other things, evident in their modulating role of global atmospheric and oceanographic processes, which result from their highly reflective surfaces and from the meltwater they produce. But most importantly, because most of their volume lies on land above sea level, any change in them has an immediate effect on the global sea-level stand. If melted entirely, these ice sheets would contribute about 70 m to the world-wide level of the oceans, of which around 10% would arise from the Greenland ice sheet alone (*Table 3.13-1*. Thus, loss of only a small fraction of this volume would already have a significant effect. A key question is whether the projected rising temperature can induce ice-dynamic processes in these ice sheets that could appreciably enhance ice discharge on time scales of the order of a century.

Climate response

Central to understanding the response of ice sheets to climate is their mass balance, that is, the difference between snow accumulation and ablation. The ablation consists of meltwater runoff, iceberg discharge, and evaporation. In essence, an ice sheet can only exist when the accumulation at its surface occurs over an area large enough to balance the mass loss at the margin. A positive overall mass budget will lead to growth of the ice sheet, whereas a negative budget implies a shrinking ice sheet. The mass-balance at the ice-sheet surface is intimately linked to the climatic conditions which prevail over the ice sheets. The most important meteorological variables are temperature, insolation, and the solid precipitation rate, which in turn depends on temperature. This link between temperature and mass balance creates a fundamental difference between the basic response of the Antarctic and Greenland ice sheets to climatic change.

The Antarctic ice sheet is located in a very cold climate, where virtually no melting occurs and precipitation amounts are restricted by low air temperature. As a result, virtually all Antarctic ice is eventually transported toward

Table 3.13-1: Physical characteristics of the polar ice sheets. Data sources: REEH et al. (1999), HUYBRECHTS et al. (2000), and other sources

	Antarctic ice sheet (grounded ice only)	***Greenland ice sheet***
Area (10^6 km^2)	*12.4*	*1.71*
Volume (10^6 km^3 *of ice*)	*25.7*	*2.85*
Volume (sea level equivalent, m)	*61.1*	*7.2*
Accumulation (10^{12} *kg/yr*)	*1830*	*522*
Runoff (10^{12} *kg/yr*)	*<10*	*297*
Iceberg discharge (10^{12} *kg/yr*)	*2072*	*235*
Mass turnover (sea level equivalent, mm/yr)	*5.1*	*1.4*
Mass turnover time (yr)	*˜15000*	*˜5000*

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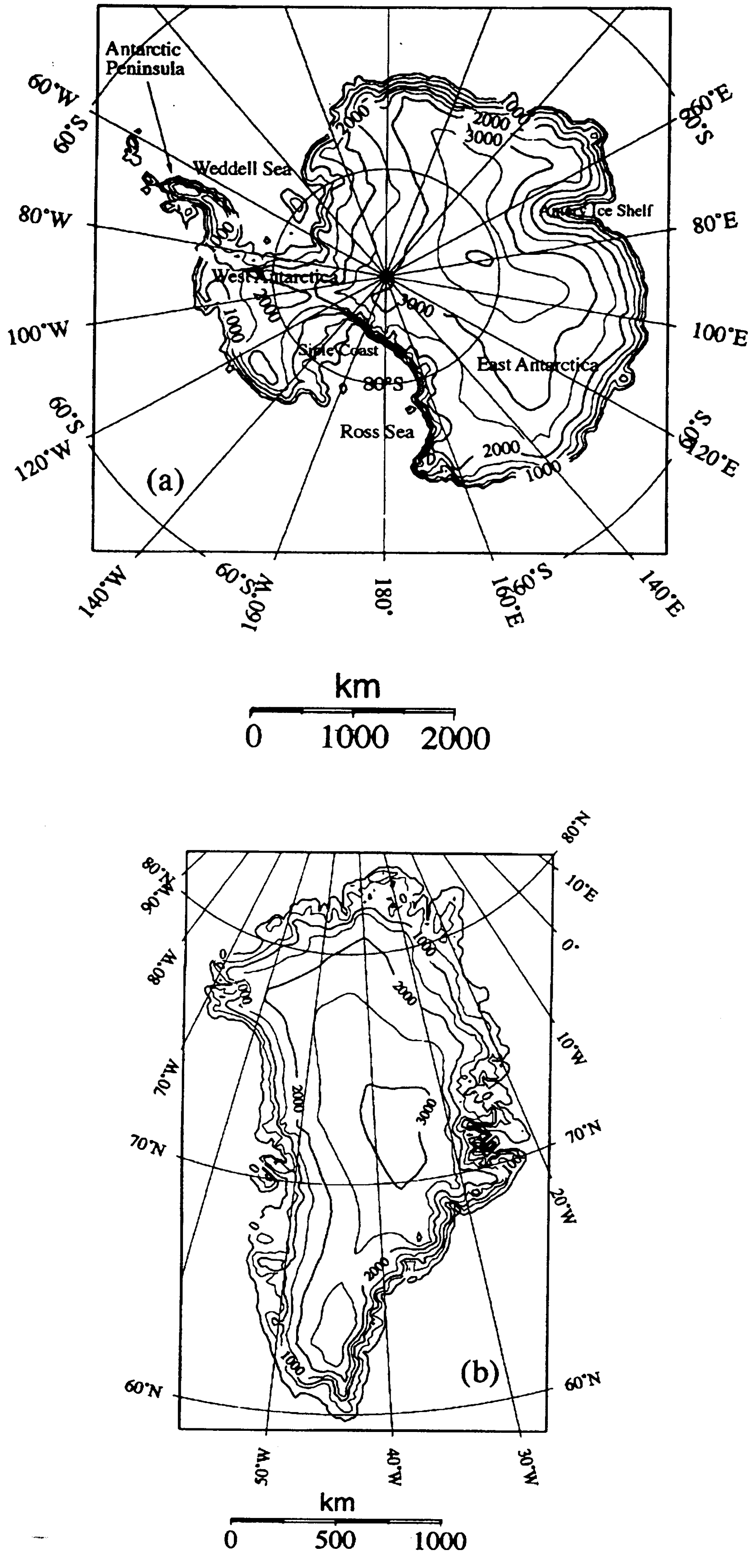


Fig. 3.13-1: (a) The Antarctic ice sheet and *(b)* Greenland ice sheets, showing the major features discussed in the text.

the sea, where it enters into floating ice shelves that experience melting or freezing at their underside and eventually break up to form ice bergs (*Table 3.13-1*). In such a cold climate, a rise in temperature is generally believed to lead to a larger surface mass balance, because the increased moisture-holding capacity of air will lead to more precipitation, but at the same time the low temperatures will prevent any significant increase of meltwater runoff.

The climate of Greenland, on the other hand, is very different from Antarctica, with a temperature difference of 10–15°C in the annual mean. Unlike the Antarctic ice sheet, the Greenland ice sheet is located in a region where temperatures are high enough to initiate widespread summer melting. As a consequence, at elevations below 1,000 m in the north and 1,600–1,800 m in the southwest, the annual ablation exceeds the accumulation, and a negative local surface budget results. Estimates suggest a roughly fifty-fifty ratio between ice mass lost by runoff and by calving. In a warmer climate over Greenland, it is likely that the increase in melting will outweigh the potential increase in snowfall rates, so that in case the calf-ice production remains constant, a more negative overall mass-balance will result.

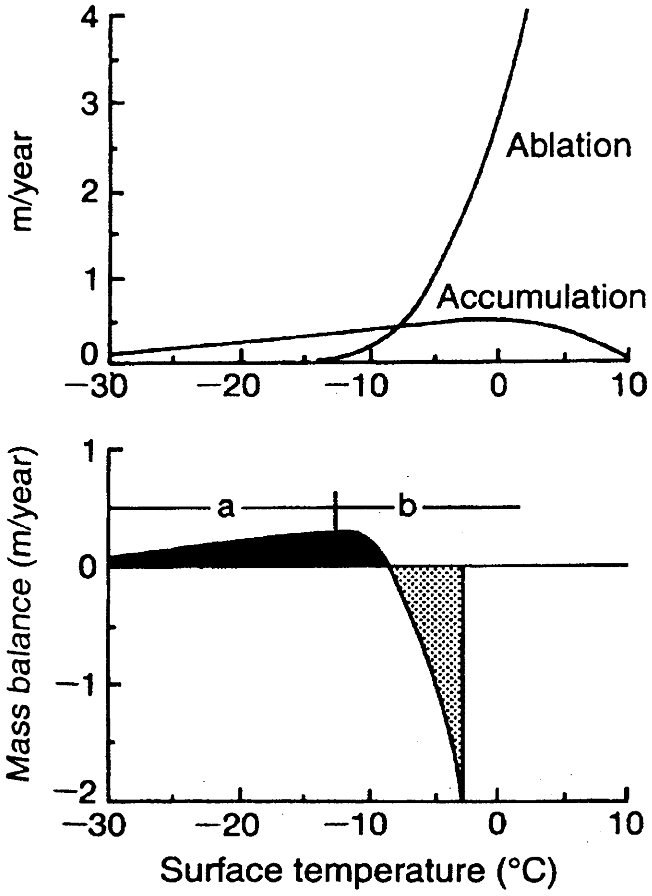


Fig. 3.13-2: Schematic dependence of ablation (evaporation and runoff) and accumulation on annual surface temperature. The dependence of annual balance changes sign, which complicates the response of ice sheets to climatic change

This differential behaviour is nicely demonstrated in a generalised surface mass-balance curve as shown in *Fig. 3.13-2*. The Greenland ice sheet is mainly in region (b), whereas the Antarctic ice sheet with its much colder climate is situated in region (a). Unfortunately, only few mass-balance measurements and only a limited number of (short) meteorological time series are available to confirm such a theoretical model in reality. Therefore much of our understanding on the interaction of the large polar ice sheets with climatic change has to be derived from theoretical models, which are based on general physical principles and try to incorporate as much of the relevant information as is available. Especially the results of the ice cores retrieved from the large ice sheets are a very valuable source of information. In this way, data from the past act as a guide to the future, though it is not by itself evident that relations which hold on the glacial-interglacial time scale can readily be applied to the problem of short-term climatic warming. Nevertheless, similar relations between mass-balance components and climatic conditions as depicted in *Fig. 3.13-2* seem to be confirmed by analyses comprising regression studies on measured accumulation and ablation data, by experiments with meteorological models, and by simulations with GCM's. Typical estimates of the sensitivity of the Greenland and Antarctic ice sheets to a 1 °C climatic warming are +0.3 and -0.3 mm/yr of equivalent sea-level change, respectively, but the scatter remains large (IPCC 1996).

Current state of balance

When discussing future changes in the volume of polar ice sheets, it is important to distinguish between the long-term »background« signal (natural variations) and the climatically induced signal in the future (anthropogenic effect). Because of their long reaction time scales (of the order of 10^3 to 10^4 years), determined by such processes as isostasy, thermomechanical coupling, and the ratio of ice thickness to yearly mass turnover, it is unlikely that the Antarctic and Greenland ice sheets have adjusted completely to their past history. Even in the absence of any present-day climatic perturbations, these ice sheets are thus expected to respond to past changes of their surface boundary conditions for a long time to come, irrespective of future forcing.

The traditional approach to the balance problem is to compare all mass gain terms with the mass loss terms and make the budget. However, with the error bars on data currently available, this procedure is not able to produce an answer that is significantly different from zero. A more promising approach involves the accurate measuring of the surface elevation of the ice sheets by remote sensing methods. Assuming that changes in density and bed topography are small or can be determined otherwise, a trend in the amount of grounded ice mass can be detected. Using satellite and aircraft laser altimetry, Davis et al. (1998) and Krabill et al. (1999) find that the area of the Greenland ice sheet above 2000 m has been nearly in balance over the last decade, with a slight tendency for growth. Below the equilibrium line, markedly different behaviour was observed, with thinning rates in excess of 2 m/yr in the south and east. These are signatures of climatic warming, but altimetry records are presently too short to confidently distinguish between a short-term surface mass-balance variation and the century time-scale ice-sheet dynamic imbalance which is of real interest.

Comparable observations for the Antarctic ice sheet cover similarly short time periods. Wingham et al. (1998) examined the Antarctic ice sheet north of 82 °S from 1992 to 1996 and found no change in East Antarctica to within ± 5 mm/yr, but reported negative trends in excess of 5 cm/yr for several drainage basins in West Antarctica. They estimated a negative balance of −6% ± 8% of accumulation for 63% of the Antarctic ice sheet, but also here it could not be concluded whether this represents a long-term trend or just a temporary accumulation deficit during the observation period. French and British researchers have reported local evidence for accumulation increases in parts of central East Antarctica and the Antarctic Pensinsula by as much as 20–30% over the last few decades, but these data do not allow to generalise over the entire ice sheet.

A different approach to the balance problem is to simulate the evolution of the ice sheets over at least one glacial cycle to remove transient effects, and to analyse the imbalance pattern which results for the present-day. The quality of such a simulation depends on how good past climatic conditions can be described and on how good the ice-sheet model deals with dynamic aspects (such as ice-temperature evolution, flow-law, etc.). Such calculations have been made for the Antarctic and Greenland ice sheets (Huybrechts and de Wolde 1999, Huybrechts and Le Meur 1999).

The results of such a simulation with recent data are shown in *Fig. 3.13-3*. The ice-sheet model employed for these experiments is three-dimensional, solves the coupled mechanic and thermodynamic equations on a fine mesh, and includes ice shelves. The forcing was derived from the GRIP and Vostok ice cores, and from the SPECMAP sea-level record. The model shows a strong response to the glacial-interglacial cycle, involving an important shrinking of both ice sheets during the last 10,000 to 15,000 years. Of relevance for their current evolution is the behaviour of both ice sheets in a window centred around the present time (*Fig. 3.13-3c*). It turns out that the Antarctic ice sheet would still be shrinking at a rate equivalent to a sea level rise of +0.39 mm/yr, because grounding-line retreat in West Antarctica has not been completed yet as environmental conditions changed from glacial to interglacial conditions some 10,000 years ago. The Greenland ice sheet, on the other hand, would according to these calculations be near to a stationary state or grow very slightly. Nevertheless, error bands remain large. This is particularly true for the Antarctic ice sheet, where small phase shifts in the forcing have a large effect on the model outcome. In all, it seems reasonable to state that our present knowledge is just too limited to confidently answer even the basic question, and to present a meaningful judgement as to whether the ice sheets of Antarctica and Greenland are at present growing, shrinking or in a stationary state.

Ice-dynamic effects

A third aspect in the discussion concerns the dynamic response of the polar ice sheets. A change in surface mass balance results in an immediate change in ice volume, but the ice sheet will respond by trying to restore the balance between mass input and mass output. This process occurs over timescales of centuries to millennia and longer. The subsequent change in the shape of the ice sheet will affect the flow, which might in turn feed back on the mass-balance components. Because of its marginal melting zone, this may lead to a potentially powerful positive feedback on the Greenland ice sheet: a smaller ice sheet implies lower elevations, which could in turn lead to even more melting. Modelling studies, however, seem to indicate that this effect becomes only important on time scales of millennia rather than on centuries. On the short-term, the opposite effect may play and ice dynamics may even counteract the static mass-balance-only effect (Huybrechts and de Wolde 1999). A first mechanism arises because surface slopes at the margin are at first steepened in response to increased melting rates. This causes the ice to flow more rapidly from the accumulation zone to the ablation zone. The resulting thickening of the upper parts of the melting zone will then reduce the total melting. A second mechanism involves reduced outflow from outlet glaciers which calve into the sea. Grounded ice flow rates at the margin depend on ice thickness to the fourth power. This leads to the surprising result that a thinning at the margin implies a lower calving flux, and thus produces an effect counteracting the increased mass loss by melting.

In Antarctica, there is the effect of increased outflow of ice streams and migration of the grounding line, the latter of which delimits the ice sheet resting on bedrock from the floating ice shelves that surround it. Any change in the position of the floatation line or the rate of outflow into ice shelves will affect sea level by changes in the amount of ice stored by the ground-based ice sheet (*Fig. 3.13-4*). Models indicate that both of these phenomena are sensitive to basal melting below the ice shelves. In the late seventies, it was argued that the West Antarctic ice sheet, with its bed so far below sea level, could be so inherently unstable that any weakening of the ice shelves or change of the grounding line could lead to a runaway situation, in which this ice sheet would disintegrate in a few centuries time. This view is still held by some (Oppenheimer 1998), but according to others the West Antarctic ice sheet may be much more robust (Bentley 1997).

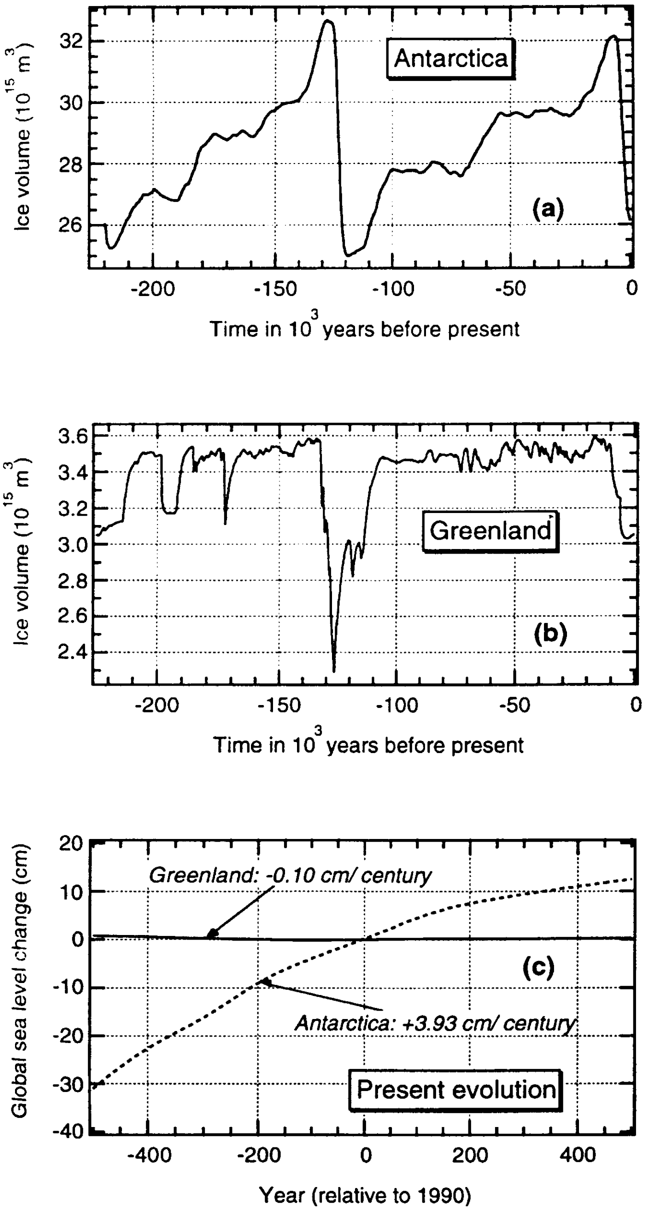


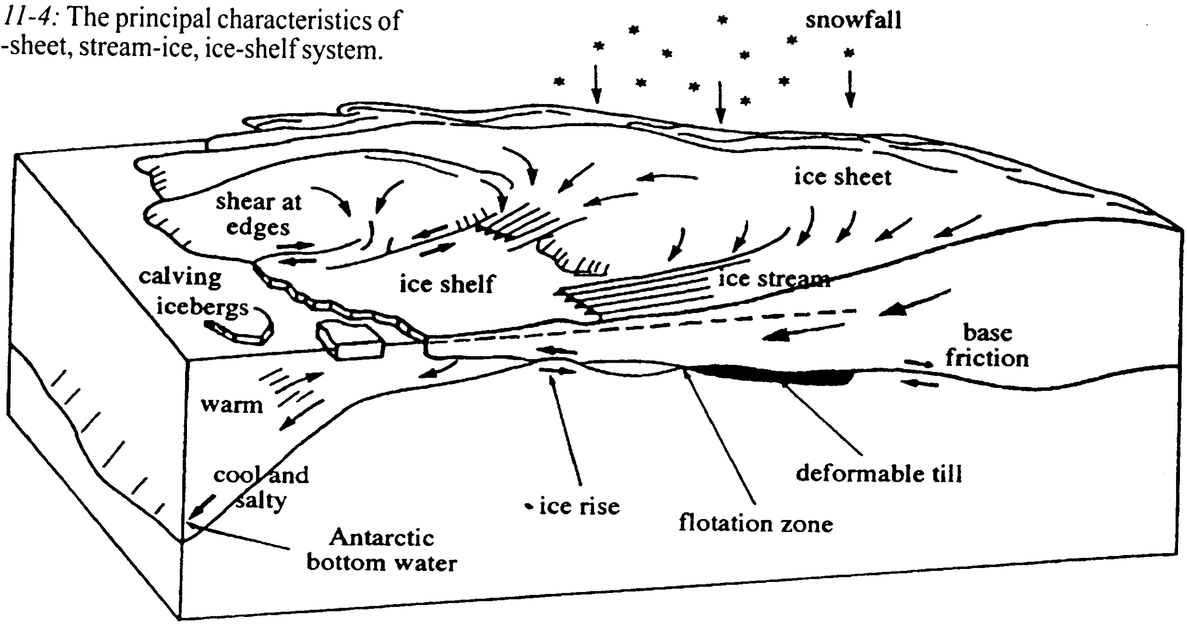
Fig. 3.13-3: Modelled evolution of Antarctic *(a)* and Greenland ice volume *(b)* over the last two glacial cycles; *(c)* displays the background trend which results for the present time. For comparison, a volume of 10^{15} m^3 of ice corresponds to a world-wide sea-level change of around 2.5 m.

The main focus of this discussion are the fast-flowing, wet-based ice streams of the Siple Coast, which discharge most of the ice into the ice shelf and whose response times to changes in the grounding line appear to be very rapid. It is now argued by some that these ice streams may even stabilise the ice sheet, because their short response times would act to remove any flux imbalance in the grounding zone. Support for this idea may come from the oscillations exhibited by these ice streams, which switch on and off on time scales of centuries in a seemingly erratic way. Force-balance studies also seem to indicate that the ice streams do not experience mechanical control from the ice shelves (Whillans and van der Veen 1997). My personal view against a dramatic collapse scenario is the fact that this would involve a speed-up of the outflow by several orders of magnitude to deliver the necessary amount of ice to the ocean to have a significant effect, but for which we have no plausible mechanism.

The IPCC projections

Ultimately, we have to rely on well-tested models to confirm or contradict the predictions and hypotheses raised in the foregoing discussion. In the IPCC (1996) report, climatic input from a two-dimensional zonal-mean energy balance climate model (De Wolde et al. 1997) was used to drive a 3-D thermomechanic ice sheet model. The climate model was in turn driven by prescribed scenarios of trace gas concentration and radiative forcing, resulting from various emission projections from the IPCC work. One set of radiative forcing scenarios assumed that aerosols (sulphate aerosols, fossil-fuel soot and aerosols from biomass burning) would remain at their 1990 levels, the second set included the effects of changes in aerosol concentrations beyond 1990. Aerosols reflect more of the incoming solar radiation which tends to lower the radiative forcing compared to the one due to the greenhouse gases alone. The sea-level projections up to the year 2100 are shown in *Fig. 3.11-5*. For Greenland, these range between 4.5 and 7.3 cm when aerosols changes are included, and between 5.2 and 18 cm when it is assumed that aerosols would remain at their 1990 levels. The Antarctic ice sheet, on the other hand, would under all scenarios tested grow slightly, basically because increased precipitation rates would dominate over increased melting rates and dynamic effects in West Antarctica remain small. The corresponding figures for sea-level change are between -5.3 cm (including aerosols changes) and -13.7 cm (constant 1990 aerosols). Remarkable is that both ice sheets display almost exactly opposite behaviour for the mid-range of the projections. This means that on a century time-scale, Antarctica and Greenland may well balance one another, at least insofar

Fig. 3.11-4: The principal characteristics of the ice-sheet, stream-ice, ice-shelf system.



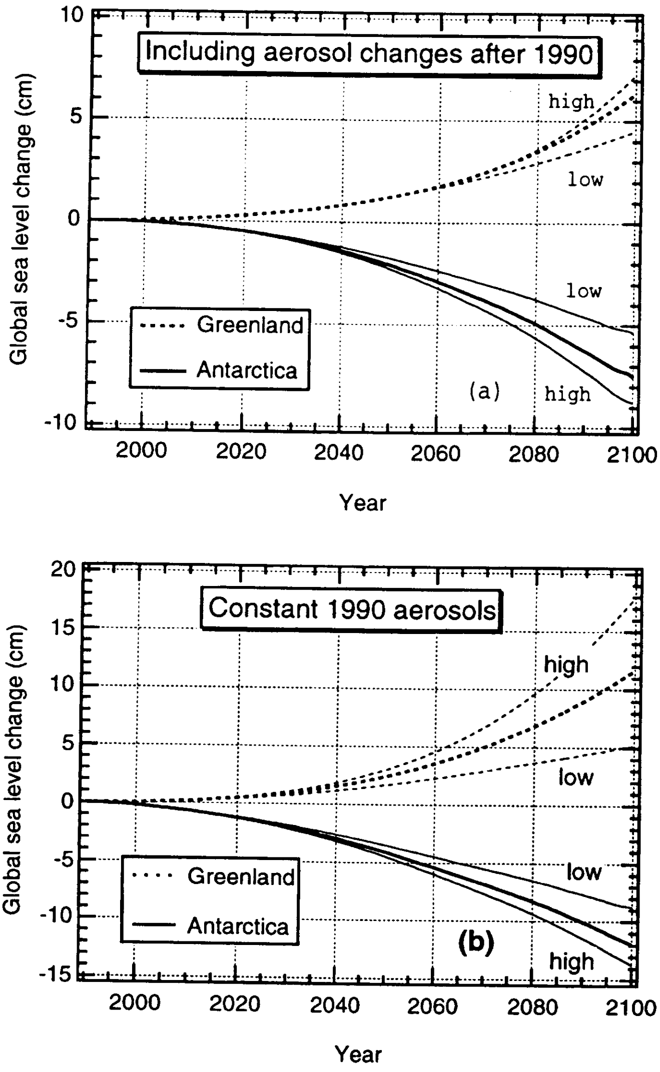


Fig. 3.11-5: Contribution of the Greenland and Antarctic ice sheets to future sea levels. These experiments were driven by IPCC (1996) climatic scenarios (high, mid, and low) based on radiative calculations which either do *(a)* or do not *(b)* include changes in atmospheric aerosols.

their response relative to the ongoing background evolution is concerned.

Nevertheless, in view of their long reaction times and huge ice volumes, this picture could change dramatically when greenhouse warming conditions were to be sustained after the 21st century. Modelling studies suggest that grounding-line retreat is then likely to become the dominant mechanism in Antarctica, and by the year 2500, the Greenland ice sheet could loose as much as a third of its volume, resulting in a total sea-level rise in excess of 3 m (HUYBRECHTS and DE WOLDE 1999)

Conclusion

The present state of understanding of the mass balance of polar ice sheets indicates that a warmer climate will lead to more melting on the Greenland ice sheet and to more accumulation over the Antarctic ice sheet, which effects would dominate over any other changes. During the next 100 years, the resulting sea-level changes from both ice sheets are projected to be relatively minor (< 10 cm), and are moreover of opposite sign. However, large uncertainties remain. Not only is there a lack of understanding of their current evolution, but there is still considerable debate regarding the possible dynamic response of, in particular, the West Antarctic ice sheet. In addition, all projections depend crucially on the climatic predictions and how these translate into mass-balance changes. Predicted patterns of temperature and accumulation change in the polar areas differ substantially among climate models and depend strongly on the emission scenarios used. Evidently, a lot more of field data as well as improved modelling is required to better understand the complex interactions between the ice sheets and the climate system and to enable more reliable predictions in a warming world"