Greenland glaciers and the 'greenhouse effect', status 1991

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Possible global climate change caused by increased 'greenhouse effect' continues to be a matter of international public concern. In particular, a warmer climate is expected to cause increased melting of the Greenland ice sheet, and a rise in world sea level. The Greenland ice sheet is therefore a potential hazard for low-lying countries. Climate warming may be apparent first, and with greatest magnitude, at high latitudes so that increased melting of the Greenland ice sheet could give early warning of global climate change. For these reasons, GGU and foreign organisations are studying Greenland glaciers in connection with the 'greenhouse effect' (Fig. 1). The present review updates the note by Braithwaite (1990).

Climate change

The most authoritative assessment of climate change is by the Intergovernmental Panel on Climate Change (IPCC) whose work was carried out by three working groups: (1) scientific assessment of climate change, (2) impacts of climate change, and (3) policy responses to climate change. The scientific assessment is published as a conventional multi-author book (Houghton *et al.*, 1990), and as an anonymous 'policymakers summary' (WMO/UNEP, 1990) which simplifies the scientific discussion but still stresses the uncertainties involved. The IPCC report includes a chapter on sea level rise (Warrick & Oerlemans, 1990) from a sub-group which involved one of the present writers (RJB). According to the IPCC assessment, sea level may rise by about 0.6 m in the next hundred years. This figure is the combined result of thermal expansion of sea water, partial melting of small glaciers around the world, and increased runoff from the Greenland ice sheet, all of which may be offset to a certain degree by increased precipitation in the Antarctic.

Will melting increase?

The IPCC estimate of sea level rise from melting of the Greenland ice sheet is based on a consensus including the estimate of 0.36–0.48 mm per year (a^{-1}) sea level rise for each degree of temperature increase (Braithwaite & Olesen, 1990a). The latter is based on energy balance models at only two locations (Braith-

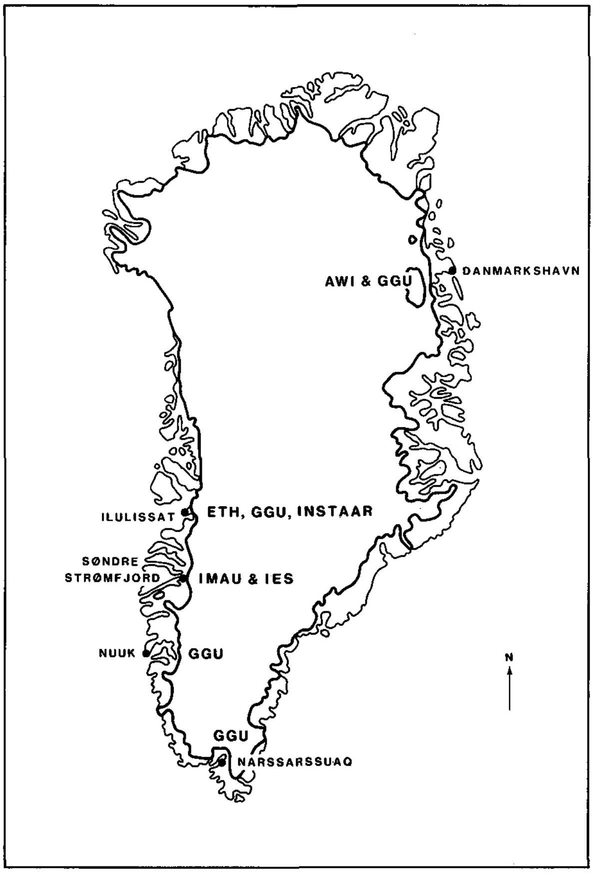

Fig. 1. Locations of recent glaciological studies (1990–1991) related to the 'greenhouse effect': AWI = Alfred Wegener Institute for Polar Research, Germany; ETH = Institute of Geography, Swiss Federal Institute of Technology, Switzerland; GGU = The Geological Survey of Greenland, Denmark; IES = Institute of Earth Sciences, Free University, Amsterdam, The Netherlands; IMAU = Institute of Marine and Atmospheric Research, University of Utrecht, The Netherlands; INSTAAR = Institute of Arctic and Alpine Research, University of Colorado, USA.

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waite & Olesen, 1990b), extrapolated to the whole ablation area of the Greenland ice sheet, while increased melting in the accumulation area is assumed to be offset by refreezing.

An advanced three-dimensional ice dynamics model for the whole Greenland ice sheet has recently been developed by a team at the Alfred Wegener Institute for Polar Research (AWI), Bremerhaven, Germany. The model is driven by mass balance variations (Reeh, *1991*) partly based on GGU's ablation model, but also taking account of an increase in accumulation with temperature which is inferred from ice cores in Greenland. Perturbation of the modelled ice sheet by higher temperatures gives a sea level rise of 0.22 mm per year per degree (Huybrechts *et al.*, 1991). This is smaller than

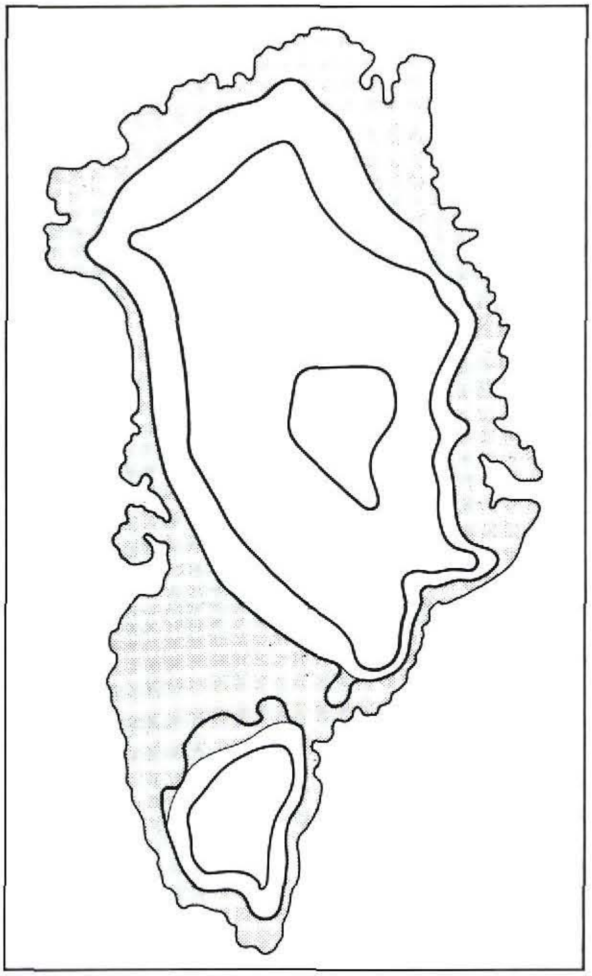

Fig. 2. Steady-state Greenland ice bodies for a temperature increase of 3°C above present temperature and with present precipitation. Redrawn from Letréguilly *et al.* (1991) with 1000 m contour lines. The larger, northern ice sheet has modelled altitude above 3200 m, the smaller southern ice cap above 2600 m.

found by Braithwaite & Olesen (1990a) because of increased accumulation in the AWI model.

The AWI model has also been used on a much longer time scale (Letréguilly *et al.*, 1991a, b) to simulate the behaviour of the Greenland ice sheet over the last 150 000 years, i.e. back to the last interglacial (Eemian) which was several degrees warmer than the present postglacial climate. The modelling results show that the Greenland ice sheet is quite stable under climate change, and would require very high temperatures over many thousands of years to disappear altogether. In particular, the model predicts the continued existence of ice from the last interglacial, and such old ice has in fact already been found at the margin of the ice sheet (Reeh *et al.*, 1987; Reeh & Thomsen, 1990; Reeh *et al.*, 1991). As an illustration, Fig. 2 shows the present ice sheet will split into two after many thousands of years with a climate 3°C warmer than present.

A few thousand years ago in the postglacial optimum, the climate was warmer than today, e.g. 1–3°C warmer in West Greenland (Funder & Weidick, 1991). The Greenland ice sheet was also somewhat smaller than now according to the long-term simulation by Letréguilly *et al.* (1991b). This is confirmed by the dating of organic material brought to the surface of the present ice sheet (Weidick *et al.*, 1990) which shows that the ice margin around Jakobshavn Isfjord 4000–5000 years ago was at least 15 km behind the present position (Fig. 3).

In conclusion, climate warming will cause increased melting, but the resulting rise in sea level may be less than estimated before because increased melting will be partly offset by increased accumulation.

Has melting increased recently?

In view of the above, it is interesting that the Greenland ice sheet appears to be growing at present rather than shrinking, i.e. sea level is currently being lowered by increased storage of water in the ice sheet.

Zwally *et al.* (1989) used satellite radar altimetry to show that the average surface elevation of the whole ice sheet south of latitude 72°N rose by 1.6 m from 1978 until 1985. There was a similar thickening of both accumulation and ablation areas, which is curious as different processes must be involved. Lingle *et al.* (1990) also confirm thickening of the ablation area over an 18-month period of satellite altimetry (1985–1986), combined with a clear annual fluctuation which presumably results from seasonal variations in accumulation and ablation. Zwally (1989) explains the indicated thickening of the ice sheet by an increase in precipitation 'under a warmer climate'.

Braithwaite *et al.* (in press) use correlations between

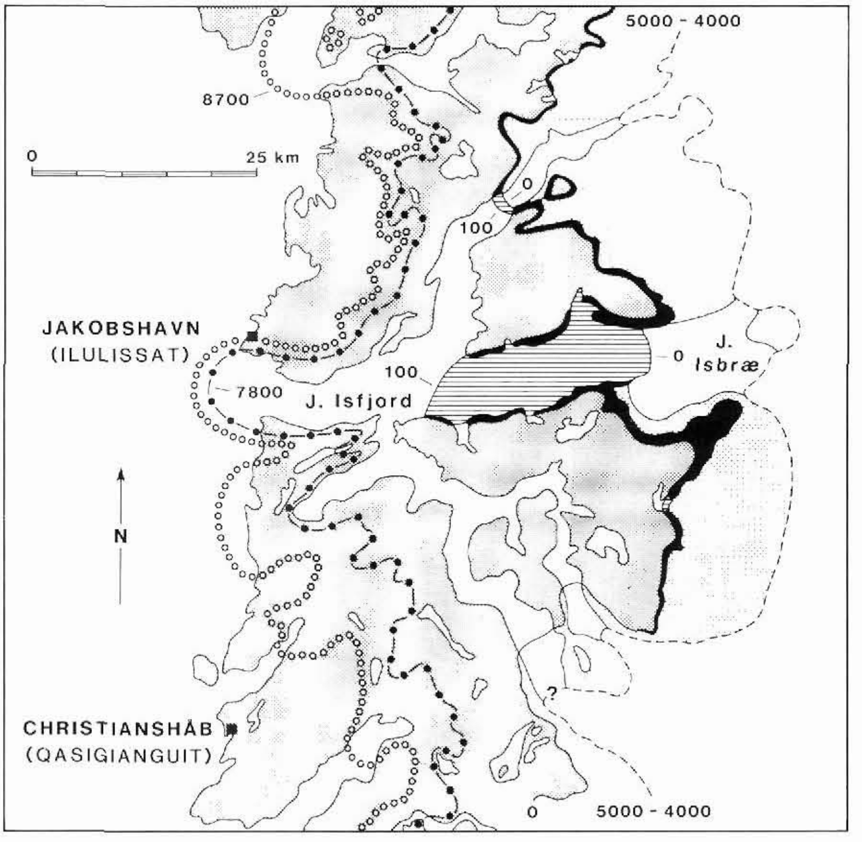

Fig. 3. Tentative reconstruction of the position of the ice margin around Jakobshavn Isbræ 4000–5000 calendar years ago, compared with those for 8700, 7800 and 100 yr B.P. (before A.D. 1950). After Weidick *et al.* (1991); J. Isfjord = Jakobshavn Isfjord; J. Isbræ = Jakobshavn Isbræ. The ice margin change between the Little Ice Age maximum and present situation [between A.D.1850 (= 100 B.P.) and 1950 (= 0 B.P.)] is shown in black for land-based areas and hatched for floating glacier fronts.

annual ablation, summer temperature, and annual precipitation from three GGU field stations to simulate ablation variations in West Greenland between 1961 and 1990. The curve from Qamanârssûp sermia is shown as an example in Fig. 4. There is a similar pattern of ablation variations for the different locations but ablation varies greatly from one year to the next, and over periods of a few years. There is, furthermore, no sign of any recent trend towards increasing ablation. The period of satellite altimetry reported by Zwally *et al.* (1989) coincides with a sequence of years with low ablation, e.g. average ablation for 1978–1985 was about 0.08 m water a^{-1} below the 30-year average. Braithwaite *et al.* (in press) conclude that Zwally's thickening of the ablation area is probably transient, which can be tested when data from satellite altimetry for the latest years become available.

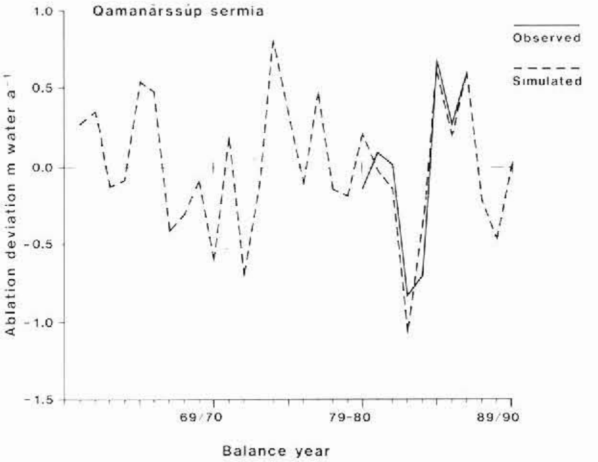

Fig. 4. Net ablation deviations at Qamanârssûp sermia over the last 30 years. The solid line is from measured data and the dashed line is calculated from climate data at Nuuk/Godthåb. From Braithwaite *et al.* (in press).

However, the reported thickening of the ice sheet (vertical change) is consistent with 'the turn of the tide' in West Greenland detected by Weidick (1991) whereby the retreat of many sectors of the ice sheet around 1950 (horizontal change) was replaced by re-advance around 1985. Weidick (1991) suggests that the general rise in summer temperature since the Little Ice Age is now being offset by an increase in precipitation, although summer temperatures in West Greenland over the past two decades have also been cooler than for the warmest decades of the present century, i.e. the early 1900s, the 1930s, and the 1950s.

Aside from the German work in North-East Greenland (Fig. 1) there is little information on ablation in the northernmost part of Greenland. However, most of the fjords in the area have a semi-permanent ice cover (sea ice) which melts completely only at rare intervals of up to several decades (Higgins, 1991). More frequent removal of fjord ice by melting would be an early indicator of climatic warming in the most northern part of Greenland but there is no sign of this yet.

In conclusion, increased melting of the Greenland ice sheet has not yet started, mainly because there has been no recent rise in summer temperatures.

International work

Concerns about sea level rise from the Greenland ice sheet have naturally lead to increased research by international groups (Fig. 1). In particular, new programmes have been launched recently by American, Dutch, German and Swiss groups: the Institute of Arctic and Alpine Research, University of Colorado near Jakobshavn/Ilulissat (Braithwaite *et al.*, 1992); the Institute of Marine and Atmospheric Research, University of Utrecht, and Institute of Earth Sciences, Free University, Amsterdam, both from The Netherlands, near Søndre Strømfjord (Bintanja *et al.*, 1990); AWI in North-East Greenland in logistic co-operation with GGU (Reeh *et al.*, 1989); and the Geographical Institute, Swiss Federal Institute of Technology in Zürich, Switzerland, near Jakobshavn/Ilulissat (Ohmura *et al.*, 1991).

The German and Dutch groups are also partners with GGU in a 10-nation project (1991–1993) on sea level changes sponsored by the European Community under the European Programme on Climatology and Natural Hazards (EPOCH) and coordinated by Prof. D. Smith, Coventry Polytechnic, U.K.

Outlook

Estimates of Greenland's contribution to sea level rise (e.g. Ambach, 1980; Warrick & Oerlemans, 1990; Braithwaite & Olesen, 1990a; Huybrechts *et al.*, 1991) still use ablation-climate models developed in West Greenland. Furthermore, present estimates of sea level rise do not take realistic account of iceberg calving which accounts for approximately half of the present mass loss of the Greenland ice sheet. Field studies of ablation-climate relationships in the remoter parts of Greenland, as well as a better understanding of iceberg calving, are therefore urgently needed for an improved assessment of Greenland's contribution to sea level under a warmer climate. Methods must also be developed to monitor the effects of climate change when it occurs.

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Meltwater refreezing in the accumulation area of the Greenland ice sheet: Pâkitsoq, summer 1991

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There is public concern that warmer climate in the future may cause extra melting of glaciers, including the Greenland ice sheet, with a resulting rise in World sea level (Warrick & Oerlemans, 1990). Recent estimates of sea level rise from Greenland include 0.36–0.48 mm/year per °C temperature rise (Braithwaite & Olesen, 1990) but much work is still needed to make reliable forecasts.

Meltwater refreezing

The refreezing of meltwater in the higher parts of the ice sheet is a key process affecting Greenland's contribution to sea level change (Polar Research Board, 1985). For example, there is a part of the accumulation area, which we call the refreezing zone, where summer temperatures are warm enough for melt to occur, but snow temperatures are cold enough for all the meltwater to refreeze. The lower boundary of this refreezing zone is the upper limit of the region from which runoff comes (the runoff limit).

Increased meltwater in the accumulation area in the future will be refrozen and will not reach the ocean. However, the refreezing process will decrease the permeability of the firn and eventually create impermeable ice, so meltwater will then run off to the ocean. There may thus be a very long time lag between the onset of increased melt and the upward migration of the runoff limit (Pfeffer *et al.*, 1991).

Several groups are interested in the refreezing problem and cooperated in fieldwork on the Greenland ice sheet at Pâkitsoq (Fig. 1) in 1991.