Environmental impact on Greenland glaciers

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The main emphasis of present investigations of Greenland glaciers concerns former climate oscillations and the variations in glacier cover related to these changes. The data acquired on climate and glacier variations provide a basis for prediction of future environmental consequences of climate changes. These include local change of ice cover and related coastal changes caused by variations in glacier load on the earth's crust in Greenland as well as global change of sea level in the oceans caused by the storage or release of melt water and calf ice from the Greenland ice cover.

The environmental and palaeoenvironmental value of such studies is clearly expressed in the recommendations of research themes for a regional research programme in the Arctic and Antarctic regions on global change (International Arctic Science Committee, 1994, p. 47). These include coordinated studies of ice sheet mass balance and global sea level change in order to "substantially reduce the uncertainties in the mass balance of the arctic ice masses, so as to better understand past sea level changes. Also the response of arctic ice masses to external forcing (including changes in atmospheric trace gases) using ice core analyses, models of mass balance and ice sheet dynamics, and geological field evidence".

In the field of applied glaciology, studies by the Geological Survey of Greenland (GGU) are essentially related to planning of hydropower utilisation in West Greenland. A major part of this energy resource is related to meltwater from the glaciers and to their dynamic conditions (Thomsen, 1986; Thomsen *et al.*, 1988). The varied disciplines applicable to glaciological investigations are shown in Fig. 1.

Background and experience for present research

The Department of Glaciology and Glacial Geology at GGU initiated the systematic mapping of Holocene changes of ice cover and connected changes of relative sea levels in the 1960s. The work was integrated with documentation and monitoring of historical and recent changes of the ice cover, especially over West Greenland (Weidick, 1976), as a Danish contribution to international geological mapping.

Studies were expanded to cover the actual ice margin of the Inland Ice at the end of the 1970s, and these investigations continued throughout the 1980s. The data acquired were primarily in order to determine the hydropower potential of West Greenland, but at the same time contributed a greatly improved insight into mass balance conditions (Braithwaite *et al.*, 1992; Braithwaite & Olesen, 1993), ice dynamics (Reeh, 1983; Reeh et *al.*, 1987; Reeh *et al.*, 1991; Huybrechts *et al.*, 1991) and mass balance modelling (Braithwaite, 1992).

With the growing interest in the environmental impact of a possible greenhouse effect on present global glaciated areas, international collaboration on the interrelationship of past, present and future climate and glacier variations have increasingly dominated the work of the Department of Glaciology and Glacial Geology during the past decade.

International collaboration

International cooperation developed gradually during continued investigations in West Greenland in the 1980s, with partners from the Alfred Wegener Institute, Bremerhaven, Germany (AWI), the Institute of Marine and Atmospheric Research, Utrecht, the Netherlands (IMAU) and Landscape and Environmental Research Group, University of Amsterdam, the Swiss Federal Institute of Technology, Zürich (ETH) and the University of Boulder, Colorado, USA.

The lack of glaciological data from North Greenland, an area considered to be very sensitive to climatic change (Bøggild *et al.*, 1994), imposed certain restrictions on mass balance models of the Inland Ice. These areas are logistically the least accessible in Greenland, and support from international and Danish sources was a prerequisite for studies.

The investigations were initiated by AWI (Germany) and GGU/Danish Polar Center (DPC) (Denmark) in 1989 (Reeh et *al.*, 1994) on the glacier Storstrømmen in North-East Greenland; field work was facilitated by cooperation with a geological mapping project in the same area (Henriksen, 1990). Storstrømmen is a downstream ablation area for the firn deposition around Summit (Fig. 2; the sites of the GISP-2 and GRIP ice cores, e.g. Taylor *et al.*, 1993), and shows surge-like dynamic behaviour. Storstrømmen preserves an ice marginal isotope climate record (Reeh *et al.*, 1994), and the area is considered a key to understand-

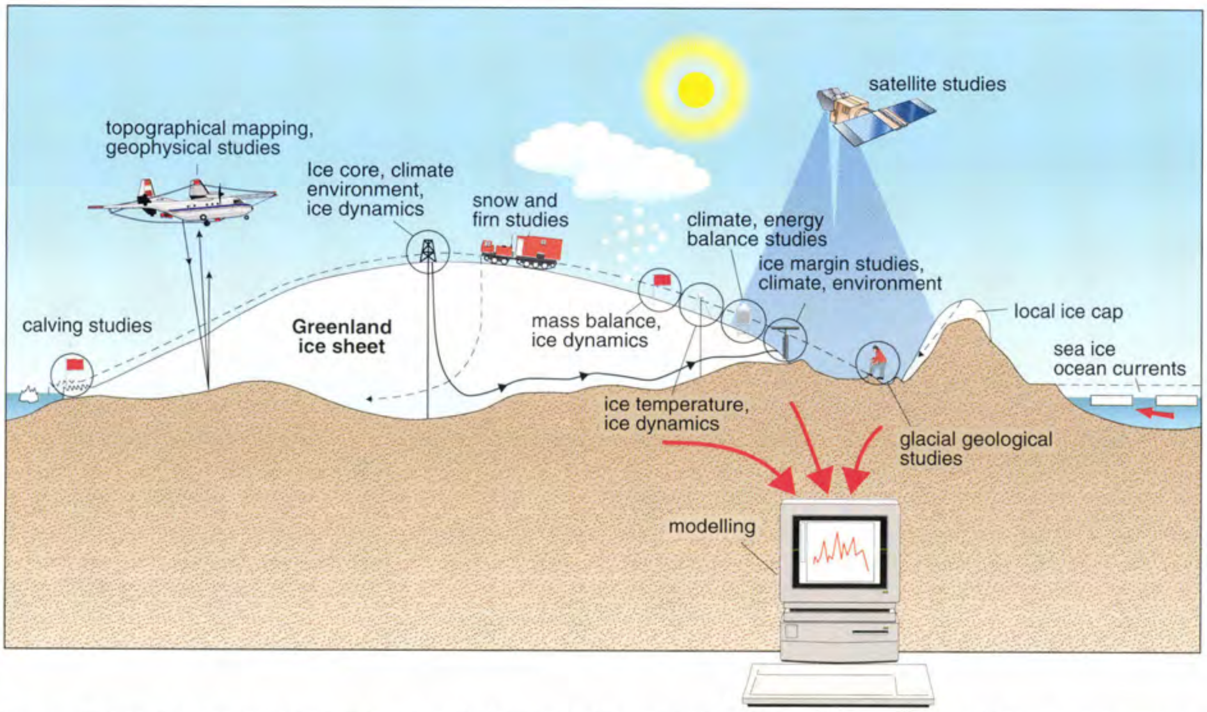

Fig. 1. Fields of glaciological research (after H. H. Thomsen). Ice marginal studies imply Quaternary geological investigations as well as measurements of the ice marginal isotopic climatic record. The dashed ice sheet surface and flow line illustrate the non-steady state of ice sheet extent and flow pattern.

ing the glaciological conditions of the North Greenland segment of the Inland Ice. Supplementary studies of climate and glaciers have been carried out since 1992 in Kronprins Christian Land *c.* 300 km north of Storstrømmen, by the same collaborating institutes (Braithwaite *et al.,* 1994; Oerter *et al.,* 1994a,b).

The Ice Age oxygen 18-isotope values ($\delta^{18}O$) at the Storstrømmen ice margin and in Kronprins Christian Land are significantly lower than those from Summit and Paakitsoq in West Greenland (Reeh *et al.,* 1993; Oerter *et al.,* 1994a, b). It is concluded that North-East Greenland ice margin isotope climate records have a specific North Greenland development not directly related to the Summit area. Since data of a more northern provenance were required for large scale glaciological modelling, a programme for investigation of Hans Tausen Iskappe was set up in 1992 and launched in 1993 (Braithwaite *et al.,* 1994). The multidisciplinary research programme on this *c.* 3000 km^2 ice cap covers the ice margin as well as the central parts where drilling of a *c.* 350 m long ice core with supplementary shallow drill cores are planned. The investigations on the ice margin are coordinated by GGU and N. Reeh (DPC), and those of the central parts of the ice cap by the Geophysical Department, of the University of Copenhagen (C. Hammer). The Hans Tausen project involves participating scientists from Denmark (noted above), Iceland (University of Iceland), Norway (University Courses at Svalbard), and Sweden (University of Lund).

A noteable extension of GGU's glaciological activities is the participation in the Norwegian Antarctic Research Expeditions (NARE) in order to gain data and experience to supplement the Greenland work. This participation began in the Antarctic summer of 1992/93 (Thomsen & Hagen, 1994) and was continued in the summer 1993/94 (Bøggild & Winther, this report).

Funding

Parts of the field work in Greenland have been carried out with the support of three major international programmes:

- The EEC programme of EPOCH (European Programme on Climatology and Natural Hazards) March 1st 1991 to February 28th 1993.
- The EEC programme on environment (Climate and Sea Level Changes and the Implications for Europe), December 1st 1992 to November 30th 1994.
- Nordic Environmental Research Programme (NMR) – Hans Tausen Ice Cap Project, January 1993 to December 1995.

Fig. 2. Location of the glaciological study areas in 1994. Approximate trend of flow lines from Summit to Storstrømmen shown by arrow.

The two EEC programmes support field projects at a variety of locations in Greenland, whereas the NMR project is a specific glaciological programme on Hans Tausen Iskappe. The work at Storstrømmen also gained support from the Commission for Scientific Research in Greenland, as well as from the Danish Natural Science Research Council.

Field activities 1994

North Greenland: Hans Tausen Iskappe

The project was initiated in 1993 (Braithwaite *et al.*, 1994) with the first major phase of field work in the summer of 1994. In the central parts of the ice cap the mobilisation for the planned deep drilling in 1995 was made by the 'ice coring group', their work included detailed investigations of surface and subsurface topography around the suggested drill site and establishment of a strain net; a test core (6 m) was obtained for $\delta^{18}O$ investigations.

At the ice margin a planned programme of mapping the Quaternary deposits along the northern flank and surroundings of Hans Tausen Iskappe was carried out by a Norwegian/Danish team. The study gave information on the Holocene change of the ice cover and of the marine sea level in the areas between Harebugt in the east and Adolf Jensen Fjord in the west (Fig. 3). A stake network, climatological stations and a radiation station were established on the ice for studies of the mass and energy balance of a 'representative' segment of the ice cap (Fig. 3). Ice surface movements were measured in the same segment and two local strain nets were established.

Sampling of firn and ice for $\delta^{18}O$ isotope studies was carried out systematically at different height intervals. Particularly detailed sampling was made near the ice margin in order to determine whether the ice cap was re-formed during the neoglacial of the last *c.* 4000 years, or was an Ice Age relict.

Field work will continue in 1995 with observations of the implemented networks on the marginal and central parts of the ice cap in connection with the deep drilling (Reeh, 1994).

North-East Greenland: Kronprins Christian Land ice margin studies

At the Inland Ice margin of south-west Kronprins Christian Land, two parallel studies were carried out in 1993. One was concerned with improvement of degree-day factors by a reconnaissance glacier and climate study (Braithwaite *et al.*, 1994). The second project, a combined climate/mass balance, ice dynamic and palaeoclimatic study, was a collaboration between AWI, GGU and DPC, and was continued in 1994. In 1994, additional measurements were made of geoelectric properties of the ice stratification for correlation with deep ice cores. The spectral reflectance of surface ice was measured in great detail, since the ablation seems to be greatly controlled by surface reflectance (Oerter *et al.*, 1994a,b). The project is mainly financed by AWI, but additional funding was provided by GGU/DPC, the Commission for Scientific Research in Greenland and by the Danish Natural Science Research Council.

North-East Greenland: Storstrømmen

Glaciological investigations on Storstrømmen were initiated in 1988, and continued in 1994 as a collaboration between AWI, DPC and GGU. The work was co-funded by the EEC programme on Environment and the Commission for Scientific Research in Greenland.

The 1994 programme was supported by the GGU operations in North Greenland in cooperation with DPC activi-

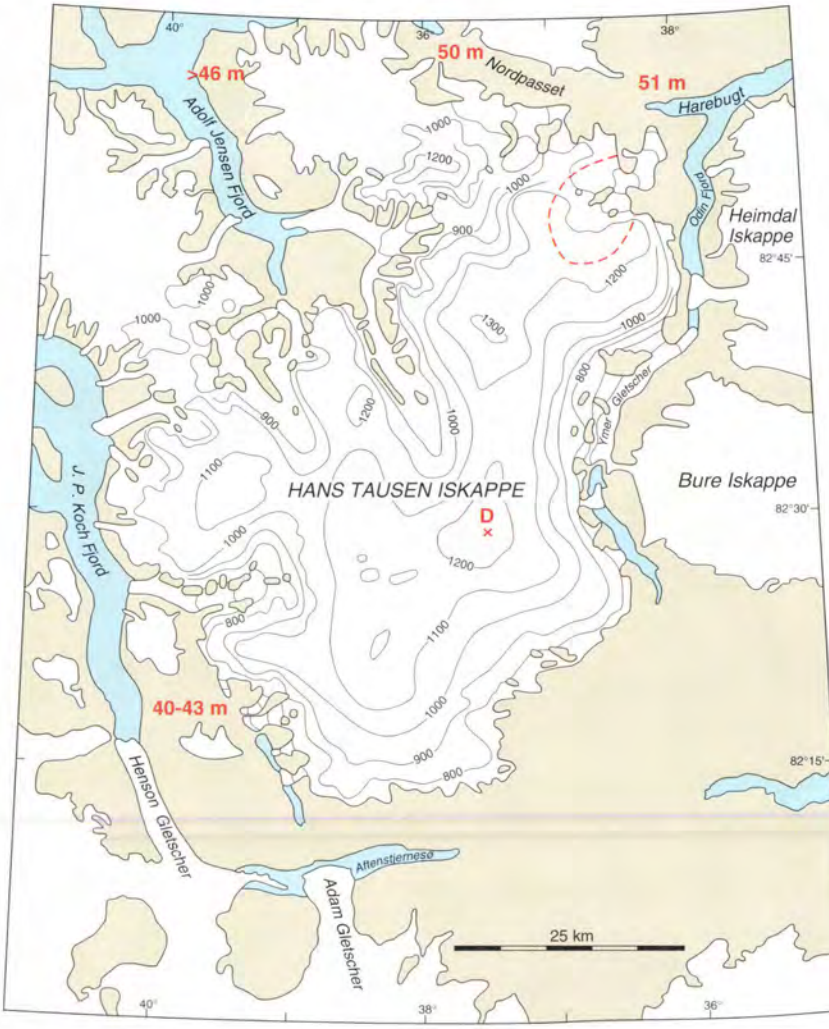

Fig. 3. Hans Tausen Iskappe. Map based on data from the National Survey and Cadastre (KMS), the Geological Survey of Greenland (GGU) and the Geophysical Department of the University of Copenhagen. D: Site of planned deep drilling. Red figures: Holocene marine limit after J. Landvik (*in* Reeh, 1994) and A. Weidick (unpublished data, 1976). Red: limit of the marginal segment investigated for mass and energy balance and ice dynamics.

ties in East Greenland; I. Hauge Anderson (DPC) provided valuable field assistance in data processing.

The aim of the detailed studies in 1994 was to analyse the microclimate in order to explain the extremely 'noisy' ablation-elevation profile which characterises Storstrømmen (Bøggild *et al.*, 1994). Five years of mass balance measurements are now available from this glacier, and they show a distinct mass balance pattern with the highest ablation rates on slopes. Satellite analyses of winter images have revealed that areas with a lack of snow accumulation in winter coincide with areas of higher melt rates in summer and are related to the steepest slopes on the glacier. A hypothetical explanation for this phenomenon, supported by preliminary processing of the data, is that gravity winds tend to accelerate where the slope is steepest and hence force more latent heat for melting to the surface. A planned continuation of the project in 1995 therefore aims at a more detailed study of climate gradients in order to quantify this phenomenon.

Measurements related to magnitude and rate of ablation and ice dynamics were continued in 1994. These included determination of spectral reflectance properties of the glacier surface at most stakes. The UV range is of particular interest in view of the recently detected ozone hole over North Greenland (e.g. Austin *et al.*, 1992; Larsen *et al.*, 1994).

The surge behaviour of Storstrømmen, most marked between 1978 and 1984 (Reeh *et al.*, 1994), has now ceased. Observations in 1994 show that the frontal regions of Storstrømmen are now being displaced to the north by the advance of the glacier immediately to the south.

In collaboration with the Danish Center for Remote Sensing, a 20 by 10 km test field has been established in an east–west cross-section of the lower parts of Storstrømmen. GPS-positioned reflectors were used as reference points for a Synthetic Aperture Radar (SAR) Repeat Track Interferometer experiment in order to determine glacier movements over large areas. This experiment is a forerunner of

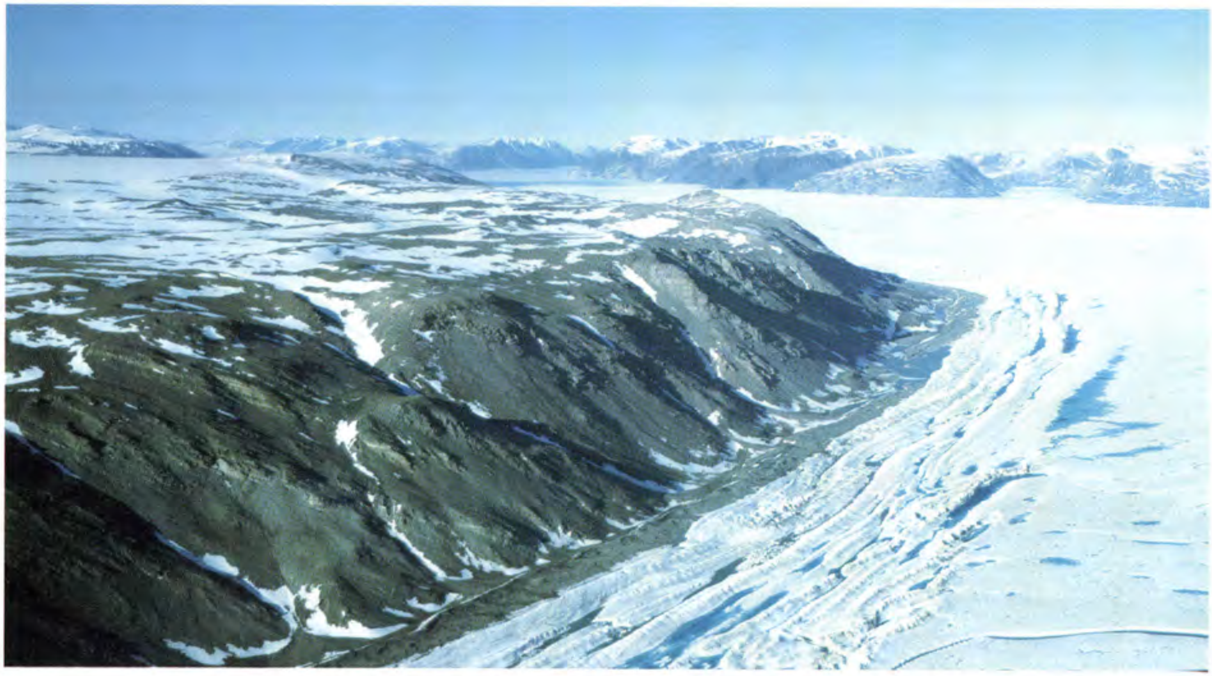

Fig. 4. Inland Ice margin in North-East Greenland. Margin of glacier in Nioghalvfjerdsfjord seen from south-west. Dijmphna Sund and Hovgaard Ø in the background. Photo J. Lautrup, July 1994.

a large scale experiment based on the use of ERS satellite SAR data for studies of glacier dynamics, to start in 1995 with support from the European Space Agency. If successful the study will be extended to the floating tongues of Zachariae Isstrøm and Nioghalvfjerdsfjord situated *c.* 180 and 220 km respectively north of Storstrømmen.

A special glacier map of the Storstrømmen area is in preparation, a joint product of the collaboration of AWI, DPC and GGU and the Universität der Bundeswehr, Frankfurt am Main, Germany.

Central West Greenland: Paakitsoq, north of Jakobshavn Isbræ

Investigations of the 'classical' ice marginal climatic record profile (Reeh *et al.,* 1991) *c.* 30 km north of Jakobshavn Isbræ were continued in the spring of 1994 (Thomsen & Reeh, 1994). Investigations on the content of dust and pollen, measurements of ice deformation and ice velocities, and studies of texture and visual stratigraphy of the ice were carried out as a collaboration between teams from DPC, GGU, AWI, the Geological Survey of Canada and Columbia University, USA. The results of the field programme are described in more detail by Thomsen *et al.* (this report).

Antarctica

GGU participation in the Norwegian Antarctic Research Expeditions 1992/93 (Thomsen & Hagen, 1994) was continued in the summer of 1993/94 as a collaboration between GGU, the Norwegian Hydraulic Laboratory, Trondheim (NHL) and the Norwegian Polar Institute (Bøggild & Winther, this report).

The investigations of 1993/94 were made in Jutulgryta, Dronning Maud Land, where studies were carried out on a blue ice field. Observations of ice temperature, water level records in wells and pump tests all indicate a widespread subsurface melt layer despite negative air temperatures and a frozen surface. Melting activity in Jutulgryta is otherwise insignificant, and this phenomenon may serve as an indicator of climate fluctuations in the area (Bøggild *et al.,* 1995).

Thematic and compilatory work

Neoglacial change of the Inland Ice margin and related sea level change

A contribution to the EEC environmental programme (1992–94) includes investigation of the neoglacial change of the Inland Ice margin and the related variations of rela-

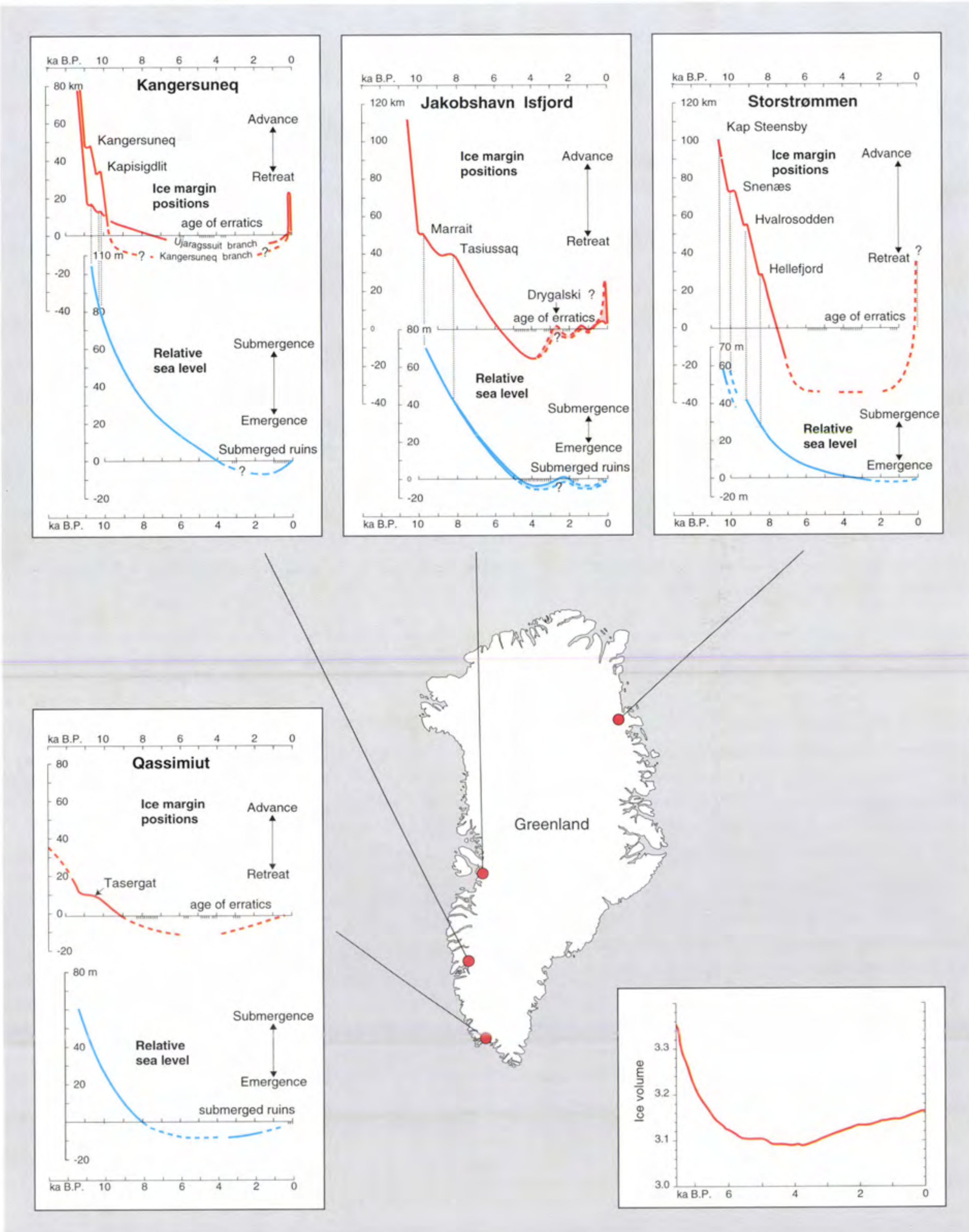

Fig. 5. Ice margin positions (red) and change of relative sea level (blue) in four key areas in Greenland. For comparison with the observed ice margin changes, the total volume change of the ice for the same period is shown at bottom right (after Huybrechts, 1994).

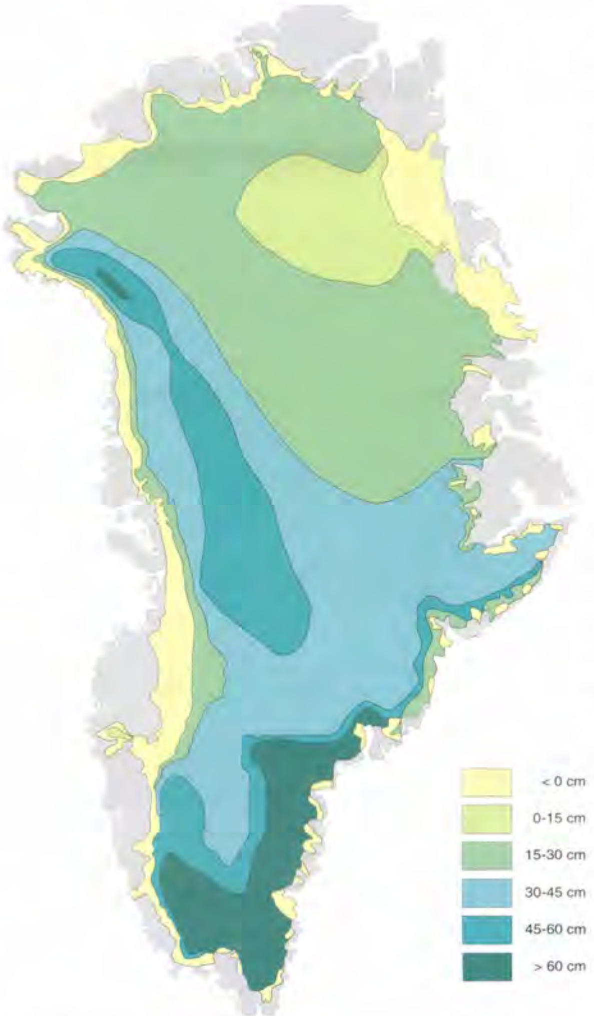

Fig. 6. Mass balance (net gain) in centimetres water equivalent for the Inland Ice accumulation area, shown for the whole ice sheet. Snow fall is low (as little as 5–10 cm) in North Greenland, and increases generally southwards where it locally exceeds 2 m accumulation. Ablation areas (areas of net loss) are shown in blue and cover only a narrow marginal area of the ice sheet. Model based on the EISMINT data base (N. Reeh and W. Starzer).

tive sea level as a consequence of fluctuations of ice load (Weidick, 1993).

The early Holocene recession of the ice cover and the connected emergence of land is well known from the investigations of the present ice-free land, whereas the late Holocene (Neoglacial) evidence of ice and sea level change is largely buried by the expanding ice cover and the submergence of land. The fragmentary evidence available is scattered and of different provenance (geophysical, geological, archaeological and historic).

Four key areas have been selected on the basis of geographical spread, amount of available information, and access to supplementary investigations, especially ^{14}C-dating (preferably AMS dating, Uppsala University, Sweden combined with conventional dating at the Carbon-14 Dating Laboratory, Copenhagen, Denmark). The location of areas and preliminary results are shown in Fig. 5. For each area the changes of ice margin (red) and heights of relative sea level (blue) are shown. Downslope trend then implies recession and land emergence and upslope trend advance and land submergence (Weidick, 1994). For comparison the volume change of the Inland Ice during the same period is shown, based on the modelling of Huybrechts (1994).

The curves of Fig. 5 at the investigated localities can be viewed as local variations of the same theme. Modelling has now reached a stage where observed changes can be explained by the modelling, or the observations can serve as a check of the modelling. However, these observations are related to only four localities; the spatial distribution of glacier change and hence the geographical distribution of deformation of the earth's crust remain poorly known. Shorelines related to the Sarqaq culture (*c.* 4000 to 2000 B.P.) point to Neoglacial deformation of the earth's crust (downbuckling at present ice margin), but the observations require better substantiation.

The near coincidence of the changes of relative sea level and extension of the ice suggests that the postglacial emergence of Greenland is not directly comparable with that of North America or Scandinavia. In the latter regions the present movement must be characterised as a plastic aftereffect of the former glaciations, whereas the Greenland deformation seems to be related to elastic response to constantly pulsating ice cover.

EISMINT (European Ice Sheet Modelling Initiative)

The EISMINT programme was initiated in 1992 in order to promote an international collaboration on modelling of ice sheet response in relation to climate change. The related database is hosted at GGU, and the work is supported by the European Science Foundation. Since the result of model calculations is no better than the quality of the input, efforts are made for a continued improvement of data and models with access to a common and continually updated database. The essential basic data comprises information on the geographical distribution of the altitude, thickness, movement, temperature, accumulation and ablation of the Inland Ice.

Work with the database at GGU is focused on development of an updated best fit model of the total mass balance of the Inland Ice for application in larger scale atmospheric models. Calculations concern the ice sheet response to future changes of global climate and its effect on sea level. A technical spin-off of these calculations has been a determination of the theoretical potential energy bound up in the Inland Ice (*c.* 470 000 GWh/yr) for the World Energy Council.

Perspectives of the glaciological work at DPC/ GGU

Applied glaciological evaluations have been made in connection with potential mining operations (e.g. the feasibility of open pit mining at the ice margin at Isukasia, central West Greenland), inflow of glacial meltwater to mine shafts (Black Angel, North-West Greenland) and subglacial mining (Malmbjerg, East Greenland). Over the past 15 years extensive applications of glaciology have been made, related to hydropower planning, and must be expected to be utilised also in the operational phase of hydropower plants.

There are also applications in respect of growing tourism and the spread of technical installations which will require better insight into glacier related hazards. Observations of avalanche destruction of installations and buildings have been recorded from Grønnedal/Kangiliinguit, Narsaq and Ammassalik. Periodic tapping of ice-dammed lakes is known from most areas; a catastrophic single outburst has been reported from the Inland Ice margin north of Narsaq town in South Greenland, where the local recession of the ice margin released an estimated $^1/_4$ to $^1/_2$ km^3 water through a narrow valley between December 1987 and May 1988 .

With an ice-covered area of *c.* 1.8 mill. km^2 glaciological preparedness is necessary, and the in-house accumulation of glaciological knowledge is a prerequisite for future Danish and Greenlandic participation in international environmental collaboration such as those described above.

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