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# Quaternary glaciation history and glaciology of Jakobshavn Isbræ and the Disko Bugt region, West Greenland: a review

Anker Weidick and Ole Bennike

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**Keywords**
Jakobshavn Isbræ, Disko Bugt, Greenland, Quaternary, Holocene, glaciology, ice streams, H.J. Rink.

**Cover**
Mosaic of satellite images showing the Greenland ice sheet to the east (right), Jakobshavn Isbræ, the icefjord Kangia and the eastern part of Disko Bugt. The position of the Jakobshavn Isbræ ice front is from 27 June 2004; the ice front has receded dramatically since 2001 (see Figs 13, 45) although the rate of recession has decreased in the last few years. The image is based on Landsat and ASTER images. Landsat data are from the Landsat-7 satellite. The ASTER satellite data are distributed by the Land Processes Distribution Active Archive Center (LP DAAC), located at the U.S. Geological Survey Center for Earth Resources Observation and Science (http://LPDAAC.usgs.gov).

**Frontispiece: facing page**
Reproduction of part of H.J. Rink's map of the Disko Bugt region, published in 1853. The southernmost ice stream is Jakobshavn Isbræ, which drains into the icefjord Kangia; the width of the map illustrated corresponds to *c*. 290 km.

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Kolonier
Annex Handelspladser
Beboede Vinterpladser
1850—51. Indbyggernes Antal tilföiet.
De vigtigste Teltepladser.
Rensdyregne.
Gammel Husplads.
Steenkullag nær Stranden.
SVARTEN HUKS
HALVÖ
Ikke undersøgt
Store iisfrie Landstrækninger af Høisletter paa c. 2000 Fod, skraat affaldende, med store mellemliggende Dale.
Umenik
Kikertarsoak
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Indlandet af Grønland bedækket og ujævnet af Iis indtil en Höide af 2000 Fod i 2 a 3 Miles Afstand fra Yderlandet og derfra svagt stigende indefter.
Ekootet
Kakkak
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Iglornait H.
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Narsak
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DISKO
Svarte Vogelberg
Arve
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Prindsens Eiland
Isungoak Næs
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Disko Bugt
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Akunak
EGEDESMINDE
Upernivik
Vester Eiland
Manermiut
Ikaktut
Sydost Bugt

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# Abstract

Weidick, A. & Bennike, O. 2007: Quaternary glaciation history and glaciology of Jakobshavn Isbræ and the Disko Bugt region, West Greenland: a review. *Geological Survey of Denmark and Greenland Bulletin* 14, xx pp.

The Disko Bugt region in central West Greenland is characterised by permanent ice streams, of which Jakobshavn Isbræ is by far the most important. The first thorough studies on the glaciology of the region were conducted over 150 years ago by H.J. Rink, who introduced the terms 'ice streams' and 'Inland Ice'. Rink's work inspired new field work, which has continued to the present, and the long series of observations are unique for an Arctic region.

Cooling during the Cenozoic led to ice-sheet growth in Greenland. A number of interglacial occurrences have been reported from the Disko Bugt region, and during the penultimate glacial stage, the Greenland ice-sheet margin extended to the shelf break. During the last glacial maximum, the ice margin probably extended only to the inner part of the banks on the continental shelf, and large floating glaciers may have been present at this time. During the Younger Dryas cold period, the ice margin may have been located at a marked basalt escarpment west of Disko Bugt.

Disko Bugt was deglaciated rapidly in the early Holocene, around 10 500 – 10 000 years before present (10.5–10 ka B.P.), but when the ice margin reached the eastern shore of the bay, recession paused, and major moraine systems were formed. With renewed recession, the present ice-margin position was attained around 8–6 ka B.P., and by *c.* 5 ka B.P. the ice margin was located east of its present position. The subsequent Neoglacial readvance generally reached a maximum during the Little Ice Age, around AD 1850. This was followed by recession that has continued to the present day.

The relative sea-level history shows a rapid sea-level fall in the early Holocene, and a slow rise in the late Holocene. This development mainly reflects a direct isostatic response to the ice-margin history.

Jakobshavn Isbræ is the main outlet from the Greenland ice sheet. It drains *c.* 6.5% of the present Inland Ice, and produces *c.* 35–50 $km^3$ of icebergs per year, corresponding to more than 10% of the total output of icebergs from the Inland Ice. The velocity of the central part of the ice stream at the front has been around 7 km/year since records began, but has nearly doubled in recent years. Other calf-ice producing glacier outlets in Disko Bugt produce *c.* 18 $km^3$ per year. The large calf-ice production of Jakobshavn Isbræ may have been initiated at about 8 ka B.P. when the glacier front receded from the iceberg bank (Isfjeldsbanken) near Ilulissat. Ice streams in inner and outer Egedesminde Dyb may have been active during the early Holocene and during the last glacial maximum.

**Authors' address**

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

E-mail: awe@geus.dk; obe@geus.dk


Fig. 1. Map of Greenland showing the localities mentioned in the text.

# Introduction

Jakobshavn Isbræ (Sermeq Kujalleq) in Disko Bugt, West Greenland, has been recognised as the king of Greenland glaciers amongst scientists and travellers in the Arctic for many decades. It is generally assumed that none of the other fast-moving outlets of the Inland Ice produce comparable quantities of icebergs. In December 2000, the Greenland Home Rule authority decided to nominate the icefjord in front of Jakobshavn Isbræ together with the surrounding areas for inclusion in the World Heritage List of UNESCO (United Nations Educational, Scientific and Cultural Organisation). The nomination report was submitted in 2003 and 'Ilulissat Icefjord' was included on the World Heritage List at the annual meeting of the World Heritage Committee in June 2004. This volume presents a comprehensive description of the region around Jakobshavn Isbræ, including the 'Ilulissat Icefjord' World Heritage site, and emphasises the importance of the region for glaciological investigations in Greenland.

## Jakobshavn Isbræ and Disko Bugt

Preparation of the Ilulissat Icefjord nomination report (Mikkelsen & Ingerslev 2002) involved perusal of the large number of scientific papers and descriptions of Jakobshavn Isbræ, its ice production and the glaciological and Quaternary history of the region. However, the nomination document was a technical report published in a limited number, and following inclusion in the World Heritage List a profusely illustrated book designed for a wider audience was produced and published in separate Danish, English and Greenlandic editions (Bennike *et al.* 2004).

The present volume documents the scientific background for the description and conclusions provided by Bennike *et al.* (2004) in the above book. The historical introduction is followed by sections that focus on the geological history, the special peculiarities of the ice cover, and the present-day status of the glacier. The increasing number of recent publications, and the wide spectrum of scientific investigations of the glacier and its environment, have necessitated an updating of the descriptive section. The opportunity is taken here to discuss and present wider conclusions on the geological history of the ice sheet and its surroundings.

In this volume, Greenlandic place names are used according to the spelling that was introduced in 1973. However, the pre-1973 spelling is retained for established stratigraphic and other terms introduced prior to this year. The Danish name of the main glacier in Disko Bugt used in most published descriptions is 'Jakobshavn Isbræ' (older version: Jakobshavns Isbræ), derived from the former name for the town on the north side of the fjord (Jakobshavn, now Ilulissat). The authorised Greenlandic name for the glacier is Sermeq Kujalleq ('the southern glacier'), but this place name is also used for several other large outlet glaciers that drain from the Inland Ice into Disko Bugt (Qeqertarsuup Tunua) and Uummannaq Fjord (Uummannap Kangerlua). To avoid confusion with other glaciers in the area with the same name, the former name 'Jakobshavn Isbræ' is retained here for the glacier, a usage that accords with most published descriptions.

The formal present-day name of the icefjord in front of the glacier is Kangia (= 'its eastern part', i.e. east of the town of Ilulissat), but other names are also used such as 'Ilulissat Isfjord', 'Jakobshavn Isfjord' and 'Jakobshavn Icefjord'. The World Heritage List uses the name 'Ilulissat Icefjord' for the entire World Heritage site, which includes land areas and parts of the Inland Ice adjacent to the icefjord.

A few other Danish place names are used in order to avoid confusion or for historical reasons. Greenland place names used are listed in the locality index (Appendix 1) at the end of this treatise; the locations of place names appear on Figs 1, 2.

## Setting

The Disko Bugt region including Jakobshavn Isbræ is situated in the central part of West Greenland, with the position of the present front of Jakobshavn Isbræ located at *c.* 69°10′N, 50°W. As the glacier is fed by an extensive sector of the ice sheet, a summary of the general morphological and glaciological features of Greenland (Fig. 3) is provided as a background for the following description. Comprehensive descriptions of the present physiography of Greenland and its relation to the complex geological history are provided by Escher & Watt (1976), Funder (1989) and Henriksen *et al.* (2000). A comprehensive account of the dynamic and climatic history of the Inland Ice is given by Reeh (1989).

The importance of the major ice stream of Jakobshavn Isbræ can best be illustrated by the size of the sector of the Inland Ice that feeds it (Fig. 3). This was estimated at


Fig. 2. Map of the Disko Bugt region showing the localities named in the text. The stippled line indicates the position of Isfjeldsbanken – the shoal at the mouth of Kangia.

between 3.7 and 5.8% of the Inland Ice, corresponding to an area of 63 000 – 99 000 km$^2$, by Bindschadler (1984). More recent estimates have increased this figure to 6.5% of the ice sheet, i.e. 110 000 km$^2$ (Echelmeyer *et al.* 1991). This extensive catchment area accounts for the greater part of the actual ice flow to the Disko Bugt region, based on Zwally & Giovinetto (2001).

## Areas and volumes

The total area of Greenland is *c.* 2.2 million km$^2$ of which the ice sheet (the Inland Ice) constitutes *c.* 1.7 million km$^2$ (Weng 1995). This latter figure also includes some minor marginal ice caps that, while contiguous with the Inland Ice proper, have their own ice dynamics. These ice caps are situated on highlands (especially in East Greenland) and usually have a thickness of a few hundred metres (Weidick & Morris 1998); their combined area only amounts to a few per cent of the total area of the Inland Ice. The Inland Ice is an approximately lens-shaped body, with a maximum thickness of 3.4 km, and with the highest elevation at Summit of 3238 m a.s.l. (Fig. 3). The Inland Ice rests in a bowl-shaped depression (Fig. 4), which in the central parts is below present sea level due to the depression of the Earth's crust caused by the load of the ice. Estimates of the volume of the Inland Ice vary from *c*. 2.6 million km$^3$ (Holtzscherer & Bauer 1954) to 2.9 million km$^3$ (Bamber *et al*. 2001; Layberry & Bamber 2001), corresponding to *c*. 7% of the world's fresh water (Reeh 1989).

## Mass balance of the Inland Ice

Snow accumulation in the central parts of the ice sheet and loss in the marginal parts govern the mass balance of the Inland Ice. The accumulation is estimated to be 500–600 km$^3$ ice per year, which until 2000 was assumed to approximately match the loss. About half of the loss was ascribed to melting, and the other half to calving. Bottom melting of floating glaciers may reduce the calf-ice production of North and North-East Greenland outlets (Reeh 1989, 1994, 1999).

Although calving glaciers are widespread along the coasts of Greenland, the main annual loss of calf ice from the Inland Ice is concentrated at a rather small number of outlets along its *c*. 6000 km long perimeter. Many of the important calving glaciers are found along the west coast of Greenland, with approximately 84 km$^3$ of the calf-ice production originating from five outlets (Table 1, Fig. 5). Four of these occur along a 300 km stretch of coast in the Disko Bugt – Uummannaq Fjord region.

The calf-ice production of Jakobshavn Isbræ is of particular importance for the mass balance of the ice sheet (Fig. 5). The production has generally been estimated to be about 35 km$^3$ ice per year, corresponding to more than 10% of the estimated total output of icebergs from the Inland Ice, but more recent estimates are higher, around 50 km$^3$ per year in 2003, according to Joughin *et al*. (2004). Jakobshavn Isbræ is considered the most active glacier in Greenland by Legarsky & Huang (2006). The reason for the large ice production is that a major part of the Inland Ice drains towards the central part of West Greenland, especially the relatively low uplands in the interior of Disko Bugt (Fig. 3).

Table 1. Calf-ice production from the five largest outlets in West Greenland

| Glacier | Latitude | Production (km$^3$/year) | Velocity (km/year) |
|---|---|---|---|
| Jakobshavn Isbræ (Sermeq Kujalleq) | 69°11´N | *c.* 35 | 5–7 |
| Sermeq Kujalleq in Torsukattak | 70°00´N | 8–10 | 2.6–3.5 |
| Sermeq Kujalleq (Store Gletscher) | 70°20´N | 14–18 | 4.2–4.9 |
| Rink Isbræ (Kangilliup Sermia) | 71°45´N | 11–17 | 3.7–4.5 |
| Gade Gletscher | 76°20´N | *c.* 10 | |

Sources: Bauer *et al.* (1968a); Carbonell & Bauer (1968); Weidick (1995).

With regard to the dynamics of glaciers, determinations of movement and calf-ice production over long time spans are rare. For Jakobshavn Isbræ and Sermeq Avannarleq in Torsukattak velocity measurements go back to 1875. It appears from scattered velocity records for the Disko Bugt

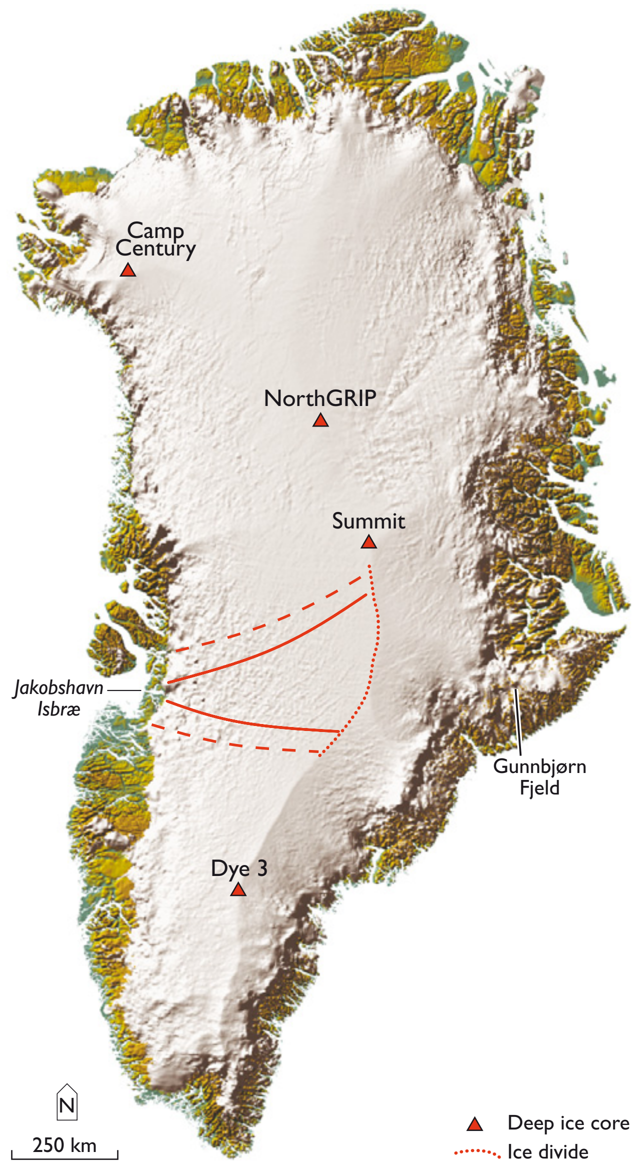



Fig. 3. Map of Greenland showing the location of Jakobshavn Isbræ and the deep cores on the Inland Ice. The approximate ice drainage area to Jakobshavn Isbræ is shown with the solid red line, and the ice drainage area to the entire Disko Bugt region with the dashed line; these are based on the flow-line map of Zwally & Giovinetto (2001). The dotted red line shows the trend of the ice divide. Summit (3238 m a.s.l.) is the highest point on the ice sheet, and Gunnbjørn Fjeld (3693 m a.s.l.) is the highest mountain in Greenland. Original map base by Simon Ekholm, reproduced with the permission of Kort & Matrikelstyrelsen (KMS) [National Survey and Cadastre], Copenhagen.

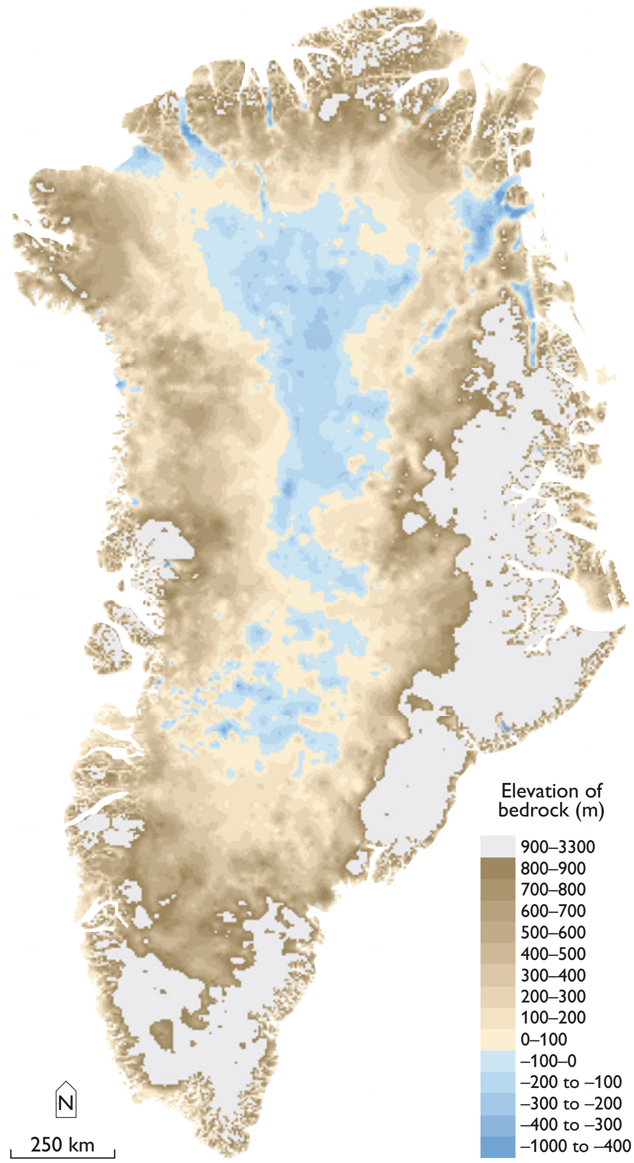



Fig. 4. Bedrock topography below the Inland Ice, from Bamber *et al.* (2001) and Layberry & Bamber (2001); data provided by the National Snow and Ice Data Center DAAC, University of Colorado, Boulder, USA. Elevations are not corrected for the present load of the glacier ice (cf. Fig. 17). The map shows the 'channel' connecting the subglacial central basin to Jakobshavn Isbræ and the Disko Bugt region.

region from the last part of the 19th and the 20th century that the glaciers have maintained a rather permanent rate of flow.

In other parts of Greenland, outlets from the ice sheet show pulsating or surging behaviour, such as Harald Moltke Bræ (Ullip Sermia) in North-West Greenland (Mock 1966), Storstrømmen in North-East Greenland (Bøggild *et al.* 1994) and Eqalorutsit Killiit Sermiat in South Greenland (Weidick 1984). More recent examples are provided by Rignot & Kanagaratnam (2006).

Over the past decades, aircrafts and satellites are increasingly being used to monitor the Inland Ice. This has led to more detailed observations on changes of velocity, calf-ice production, ice elevation and frontal positions. This development coincided with dramatic changes in the marginal parts of the ice sheet. Marked thinning and recession have been reported for many outlets in Greenland (Rignot & Kanagaratnam 2006). The velocity of many glaciers has increased, and the ice-sheet mass deficit changed from 90 to 220 $km^3$ per year between 1996 and 2005. In East Greenland, Kangerlussuaq Gletscher (Fig. 1) accelerated 210% from 2000 to 2005, and its front receded 10 km. With its velocity of 13–14 km/year it is now the fastest glacier in Greenland. Helheimgletscher farther south accelerated 60% and receded 5 km. In 2001, the velocity of this glacier was measured to be *c.* 8 km/year (Thomas et al. 2001). In West Greenland, Narsap Sermia accelerated by 150% from 2000 to 2005 while Jakobshavn Isbræ accelerated by 95% and receded *c.* 10 km. The velocity of Jakobshavn Isbræ was 12.6 km/year in 2003 (Joughin *et al.* 2004).

The marked flow-velocity increase is considered to be related to global warming, which leads to increased melting and sliding in the marginal parts of the ice sheet (Krabill *et al.* 2000, 2004). A thinning of around 2 m per year is reported for marginal parts of the Inland Ice, which is scarcely matched by a snow accumulation increase of 5–6 cm per year in the central parts of the ice sheet (Alley *et al.* 2005; Johannesen *et al.* 2005; Dowdeswell 2006; Rignot & Kanagaratnam 2006). However, whereas Jakobshavn Isbræ has maintained the high frontal velocity for several years, the velocity increase of other glaciers (Kangerlussuaq Gletscher and Helheimgletscher in eastern Greenland) seems to have been a short-lived event as the velocity and discharge have decreased since 2006 (Howat *et al.* 2007; Truffer & Fahnestock 2007).

The net loss of ice from the Greenland ice cover plays an important role in global sea-level rise, and therefore more detailed investigations of the causes for the marked changes in Greenland are required to assess and model ongoing and future changes. The recently observed changes may lead to a new stable situation, but if the changes continue they may eventually lead to the disappearance of the Inland Ice (Alley *et al.* 2005). However, we note that the Inland Ice did not disappear during the Eemian, even though temperatures were around 5°C higher than at the present.

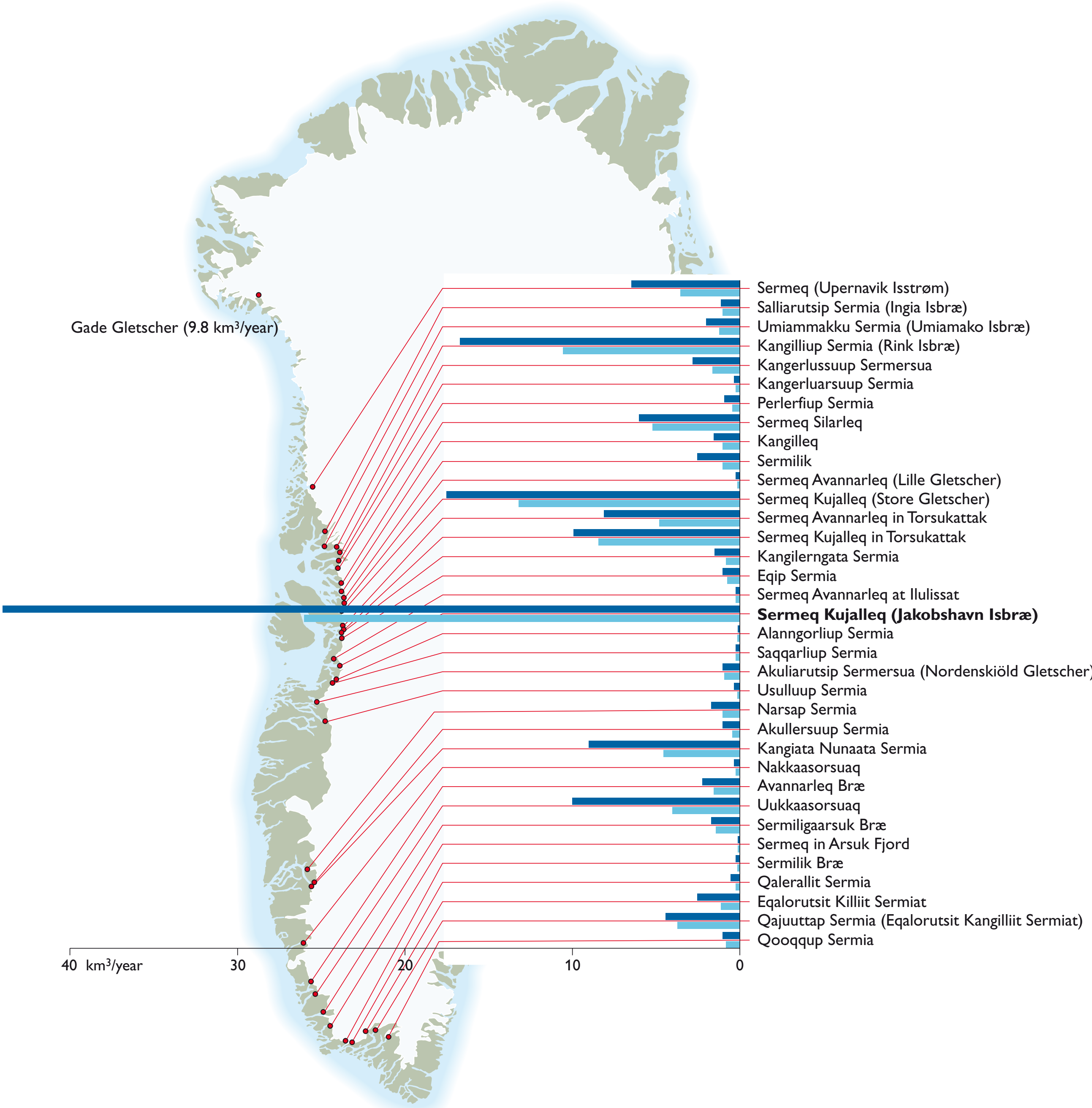



Fig. 5. Estimated maximum (dark blue) and minimum (pale blue) calf-ice production from glaciers along the west coast of Greenland. Jakobshavn Isbræ (Sermeq Kujalleq) is clearly in a class of its own (from Weidick *et al.* 1992). The data are based on Bauer *et al.* (1968a) and Carbonell & Bauer (1968), and hence do not consider the dramatic change in calf-ice production after *c.* A.D. 2000.

## Gross features of the coastland and major drainage of the ice sheet

At the present day, the Inland Ice is separated from the sea by a coastal strip of more or less ice-free land, which is up to 300 km wide. The outlets from the Inland Ice to the sea are, for the most part, restricted to fjords that cut through the coastal strips of ice-free land. Exceptions are found in North-West Greenland, in Melville Bugt (Qimusseriarsuaq) and in the Kane Basin, where large parts of the ice sheet margin reach the sea. The high alpine mountains of eastern Greenland, with peaks up to 3693 m (Gunnbjørn Fjeld at 68°55´N, 29°53´W, Fig. 3) form a topographic barrier that is in contrast to the widespread hilly uplands of western Greenland. The general topographic fall from this high mountainous barrier is to the west, and thus the main ice drainage is towards the west.

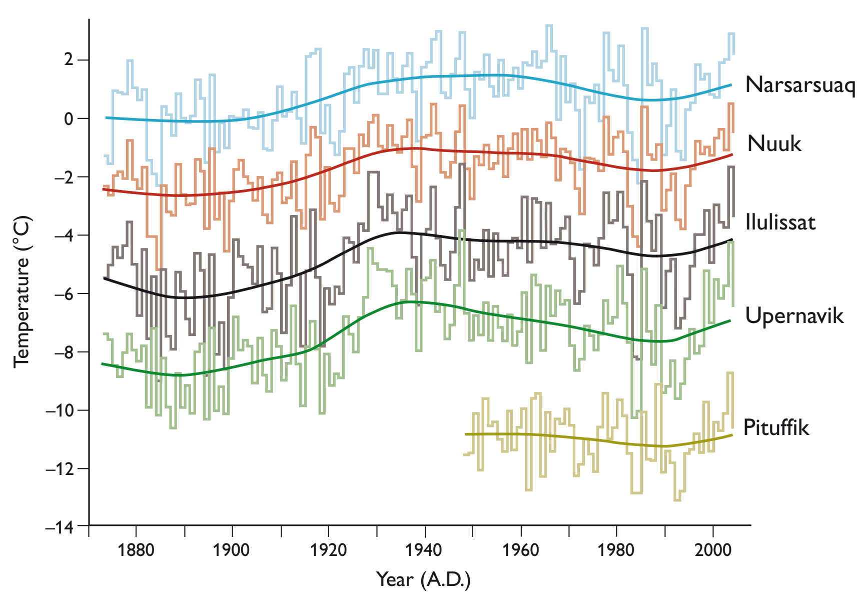
Offshore Greenland, continental shelves and slopes of variable width border the deep sea. The width of the shelf varies from 50 to 300 km, with the greatest extent off Jøkelbugten in North-East Greenland, off Kangerlussuaq in South-East Greenland, and off Disko Bugt in West Greenland. The water depth over the shelf is mainly between 100 and 300 m, except off South-East Greenland where large shelfs areas are found at 300–400 m below sea level. The total area of the continental shelf is estimated to be *c.* 825 000 $km^2$ (Henriksen *et al.* 2000). Sinuous troughs, 600–1000 m deep, cut through the shelf at intervals and extend from fjord systems or depressions to the continental slope. Their origin is connected with drowned valleys of Neogene age (Pelletier 1964) that were over-deepened and transformed by glacial erosion during the ice ages. Quaternary marine sediments and till cover large areas of the shelf. Ridges and areas of coarse sediments on the banks are interpreted as marginal deposits that were formed at advanced positions of the ice-sheet margin during the ice ages.

## Present climate

A high pressure system usually prevails over the Greenland Inland Ice at the present day. The high landmass of Greenland tends to split eastward-moving low pressure systems approaching from the south-west into two separate depressions, one travelling north along West Greenland and one travelling up along the east coast of Greenland. In addition, a number of depressions also approach West Greenland from the Hudson Bay region; most precipitation in West Greenland is related to the passage of low pressure systems (Hansen 1999). The climate along the outer coast in eastern and southern Greenland is affected by the East Greenland Current that transports large amounts of sea ice from the Arctic Ocean down along the coast of East Greenland, around Kap Farvel, and northwards up to the Paamiut area at *c.* 62°N on the west coast. Due to the relatively warm current washing certain stretches of West Greenland, parts of the coastal region are open for ship traffic, even in winter. The Disko Bugt region and areas to the north are usually covered by sea ice during the winter. In the summer, western Greenland up as far as the Thule area is nearly ice-free, with the exception of calf ice from the Inland Ice outlets (Buch 2002).

Precipitation in Greenland shows a marked general decrease from south to north. More than 2500 mm/year is recorded in southern Greenland, decreasing to less than 150 mm/year in the interior of Peary Land in northern Greenland (Reeh 1989). In all parts of Greenland, a decrease in precipitation is apparent from the outer coast to areas near the ice-sheet margin. The latter areas are characterised by a continental type of climate; mean annual precipitation at Kangerlussuaq airport in West Greenland at 67°N is around 150 mm, and at Ilulissat at 69°13´N it is around 270 mm (Cappelen *et al.* 2001). On the western slope of the Inland Ice at around 70°46´N, observations indicate

Fig. 6. Annual mean temperatures between 1873 and 2004 for five stations in West Greenland, including Ilulissat (redrawn from Cappelen 2005). The smooth curves were created using a Gauss filter; locations of the stations shown on Fig. 1.



a mean annual precipitation of *c*. 600 mm that is thought to be related to the relatively easy access of humid air masses passing through Disko Bugt (Reeh 1989); this results in lowering of the glaciation level in this region (Humlum 1985, 1986). The average accumulation for the entire ice sheet is around 31 cm water equivalent annually (Ohmura & Reeh 1991), with a general south to north decrease.

In West Greenland, the mean annual air temperature decreases from +0.6°C at Qaqortoq (61°N) to –3.9°C at Ilulissat (69°N) and –11.1°C at Thule Air Base at 77°N (Cappelen *et al*. 2001; Box 2002). These values are based on data from meteorological stations situated close to sea level. Historical data from these and other meteorological stations show a rise in temperature between *c*. 1880 and *c*. 1950, followed by cooling of 1–2°C between *c*. 1950 and *c*. 1990 and a subsequent marked warming (Fig. 6). Data from a network of automatic weather stations indicate that the mean annual air temperature for the central parts of the ice sheet was around *c*. 2°C higher during the time period 1995–1999, as compared to the period 1951–1960. At an elevation of 1000–2000 m, the temperature increase was only *c*. 1°C (Steffen & Box 2001).

On the ice sheet itself, the mean annual temperature at the surface varies between 0°C and –32°C, according to elevation and geographical location. The temperature increases with depth in the ice body and can reach the pressure-melting point (–2.6°C for 3000 m thick ice) due to geothermal heat and heating caused by ice deformation. It is generally believed that most glacial erosion takes place near the margins of the ice sheet. However, cold bed conditions are found at high, elevated areas with thin and almost stagnant ice. In such areas, the ice cover will protect the subsurface, rather than erode it (Reeh 1989).