Annals of Glaciology 35 2002

Comparison between Greenland ice-margin and ice-core oxygen-18 records

NIELS REEH,[1,4] HANS OERTER,[2] HENRIK HØJMARK THOMSEN[3]
[1] *The University Courses on Svalbard (UNIS), P.O. Box 156, N-9171 Longyearbyen, Norway*
E-mail: nr@emi.dtu.dk
[2] *Alfred-Wegener-Institut für Polar-und Meeresforschung, Postfach 120161, D-27515 Bremerhaven, Germany*
[3] *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen, Denmark*
[4] *Ørsted-DTU, Electromagnetic Systems, Technical University of Denmark, Building 348, Ørsteds Plads, DK-2800 Kgs. Lyngby, Denmark*

ABSTRACT. Old ice for palaeoenvironmental studies retrieved by deep core drilling in the central regions of the large ice sheets can also be retrieved from the ice-sheet margins. The $\delta^{18}O$ content of the surface ice was studied at 15 different Greenland ice-margin locations. At some locations, two or more records were obtained along closely spaced parallel sampling profiles, showing good reproducibility of the records. We present ice-margin $\delta^{18}O$ records reaching back to the Pleistocene. Many of the characteristic $\delta^{18}O$ variations known from Greenland deep ice cores can be recognized, allowing an approximate time-scale to be established along the ice-margin records. A flowline model is used to determine the location on the ice sheet where the margin ice was originally deposited as snow. The Pleistocene–Holocene $\delta^{18}O$ change at the deposition sites is determined by comparing the $\delta^{18}O$ values in the ice-margin record to the present $\delta^{18}O$ values of the surface snow at the deposition sites. On the northern slope of the Greenland ice sheet, the Pleistocene–Holocene $\delta^{18}O$ change is about 10‰ in contrast to a change of 6–7‰ at locations near the central ice divide. This is in accordance with deep ice-core results. We conclude that $\delta^{18}O$ records measured on ice from the Greenland ice-sheet margin provide useful information about past climate and dynamics of the ice sheet, and thus are important (and cheap) supplements to deep ice-core records.

INTRODUCTION

$\delta^{18}O$ records from the large ice sheets of the polar regions have provided rich information about climate and environmental changes during the past ~400 000 years (400 kyr) as demonstrated by the results of the deep ice-core drilling programmes carried out in central Greenland (e.g. Dansgaard and others, 1982, 1993) and Antarctica (Lorius and others, 1985; Jouzel and others, 1987). The old ice found at depth in the central regions of the ice sheets can also be retrieved from the ice-sheet margin (Lorius and Merlivat, 1977; Raynaud, 1977; Reeh and others, 1991, 1993). This is illustrated by Figure 1, which shows particle paths in a cross-section of an ice sheet. The higher in the accumulation area the ice was originally deposited, the deeper into the ice sheet it will sink, and the nearer to the ice edge it will resurface in the ablation area. If basal temperatures never reached the melting point, and if basal ice was never subject to folding or displacement along shear planes, a complete sequence of all deposited layers would occur at the surface in the ablation area, with the oldest ice closest to the ice edge.

From 1985 to 1994, the $\delta^{18}O$ distribution of the surface ice has been studied at 15 different locations on the Greenland ice-sheet margin. Ice samples were collected in profiles perpendicular to the ice margin. At some locations, two or more records were obtained along closely spaced parallel sampling profiles in order to study the reproducibility of the records. The sampling frequency ranged from spot sampling at distances of 1–100 m to continuous sampling (20 cm sample length) over a distance of >450 m. Altogether, 28 $\delta^{18}O$ records have been established from the Greenland ice margin. In this paper, emphasis is put on records (19 out of 28) that reach beyond the Pleistocene–Holocene transition 11.5 kyr ago according to the time-scale established for Greenland deep ice cores (Johnsen and others, 1992b). A relative chronology for the ice-margin records is established by correlating characteristic $\delta^{18}O$ features in the ice-margin records with similar features in Greenland deep ice-core records. A flowline model is used to pinpoint the locations on the ice sheet where the ice from the Pleistocene–Holocene transition was originally deposited as snow. The magnitude of the Pleistocene–Holocene $\delta^{18}O$ change at the deposition sites is then

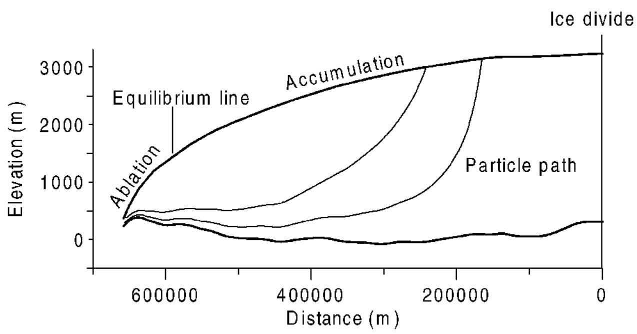

Fig. 1. Cross-section of an ice sheet, showing particle paths connecting snow-deposition sites in the accumulation zone with locations where the ice resurfaces in the ablation zone.

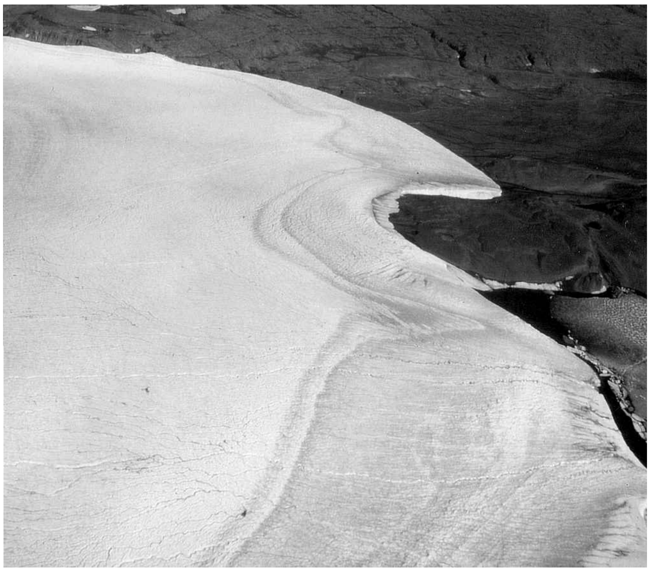

Fig. 2. Ice-margin sampling site in Kronprins Christian Land. Alternating light- and dark-coloured bands running parallel to the ice margin are visible. The wide dark band nearest to the ice edge is approximately 1 km wide and consists of pre-Holocene ice. The thin light and dark bands adjacent to the wide dark band are the Bølling–Allerød/Younger Dryas climate oscillation. The light-coloured ice to the left is Holocene ice.

Fig. 3. Location of Greenland ice-margin sampling sites (dots) and deep ice-core drilling sites (crosses).

determined by comparing the δ^{18}O values of the ice-margin profiles to the present δ^{18}O value of the surface snow at the deposition sites. The geographical distribution of the δ^{18}O change and the length of the δ^{18}O records are compared to information from Greenland deep ice-core records.

CHARACTERISTICS OF ICE-MARGIN SAMPLING SITES

The Greenland ice-margin records were sampled in summer seasons from land-based ice margins often from sectors with divergent flow (stagnation zones). In the summer, the surface of such ice margins consists of glacier ice that ablates by melting. The annual ablation rate at the study sites ranges from almost zero at the high-altitude sites in northeast Greenland (Grandjean Fjord, Dronning Louise Land) to 1–3 m of ice at the sites at lower elevations. The surface consists of bubbly glacier ice, and surface irregularities with length and height scales of typically 2–5 and 0.5 m, respectively, are a common occurrence. A photograph of a typical δ^{18}O sampling site is shown in Figure 2. Alternating dark- and light-coloured bands running parallel to the ice margin are clearly seen in the photograph. The light ice generally consists of coarser crystals than the dark ice. Cryoconite holes of varying diameter (from a few mm to >1 m) and depths (0.1–0.5 m) containing dark material (dirt and blue-green algae) are more abundant in the light-looking bands than in the dark bands, where the dirt particles seem to be more uniformly distributed in the surface layer. This difference in dirt distribution apparently causes a difference of the surface structure that most likely explains the different colouring of the surface. Blue bands, 1–100 cm wide striking roughly parallel to the ice margin often over distances of several hundred metres, are also common. The blue bands dip up-glacier at a steep angle. They consist of clear coarse-grained ice with δ^{18}O values several per mil higher (i.e. enriched in the heavy-isotope δ^{18}O) than those of the adjacent ice. Apparently, the only discontinuity in the δ^{18}O record caused by a blue band is the anomalous δ^{18}O value of the blue-band ice itself. No explanation is known for the origin of blue bands and the δ^{18}O anomaly. Together with thin dirt bands (silt fraction), the blue bands form part of the large-scale foliation pattern at the surface seen in Figure 2.

SAMPLING PROCEDURE

The ice samples were collected using a chisel after removal of the loose radiation crust (~5 cm) with an ice axe. The ice was filled into 50 mL plastic bottles with tight lids, giving a 10–30 mL melted water sample. After shipment to the analysis laboratory (Department of Geophysics, Niels Bohr Institute, University of Copenhagen, or Alfred Wegener Institute for Polar and Marine Research, Bremerhaven), the samples were either measured immediately or stored at a temperature below −10°C until analyzed.

δ^{18}O RECORDS

The location of the Greenland ice-margin sampling sites is shown on the map in Figure 3. Information on geographic location and length of the profiles, spacing and number of samples, length of pre-Holecene section and time-span covered by the profiles is summarized in Table 1. The mean δ^{18}O values of the early-Holocene and Last Glacial Maximum (LGM) sections of the profiles are displayed in Table 2. We use 11.5 kyr as the date of the transition from Younger Dryas to pre-Boreal, and ~20 kyr for the LGM. Standard deviations of the means are calculated if a sufficient number of δ^{18}O values is available. If there are only one or two δ^{18}O values, the standard deviation is not listed. In this case, the uncertainty of the δ^{18}O value is estimated to be ±1‰.

Table 1. Greenland ice-margin $\delta^{18}O$ records

Site	*Sampling year*	*Location*	*Elevation* m	*Profile length* m	*Length of pre-Holocene section* m	*Number of samples*	*Sampling spacing* m	*Estimated time-span* kyr	*Source*
Hans Tausen Iskappe A	1994	82°53.0′ N, 36°07.5′ W	150–200	200	0	40	5		
Hans Tausen Iskappe B	1995	82°27.4′ N, 36°27.9′ W	750–800	2000	0	301	1–10		
Kilen	1985	81°18.2′ N, 14°14.4′ W	400	180	0	10	20	?	
Warming Land 1	1985	81°10.8′ N, 51°07.0′ W	700–790	830	670	13	50–100	?	1
Warming Land 2	1985	81°10.8′ N, 51°07.0′ W	685–795	765	530	13	50–100	?	1
Warming Land 3	1985	81°10.3′ N, 51°09.6′ W	820–932	725	385	12	50–100	?	1
Warming Land 4	1985	81°10.3′ N, 51°09.6′ W	825–950	810	430	15	50–100	?	1
Kronprins Christian Land K	1993/94	79°54.7′ N, 24°06.3′ W	330–390	1950	700	1243	1–5	>20	2
Kronprins Christian Land KS	1993	79°51.2′ N, 24°12.0′ W	500	455	450	183	2.5	>20	2
Kronprins Christian Land KS	1994	79°51.2′ N, 24°12.0′ W	500	690	450	1187	0.2–0.5	>20	2
Inglefield Land	1993	78°35′ N, 68°00′ W	?	1000	250	150	5–50	?	3
Storstrømmen N	1989/90	77°11′ N, 21°57′ W	160–220	2200	1700	2436	0.5–1	>100	4
Storstrømmen NS	1989/90	77°11′ N, 21°57′ W	160–200	1524	1320	1195	1–2.5	~80	4
Nuna Ramp	1986	76°46.5′ N, 67°15′ W	560–590	1001	0	95	4–20	~2.5	5
Dronning Louise Land	1989	76°45′ N, 25°40′ W	1300	300	0	117	2.5		
Tuto Ice Ramp	1986	76°24.5′ N, 68°16.8′ W	540–585	885	0	82	5–20	0.4–1.4	5
Grandjean Fjord	1989	75°11′ N, 23°25′ W	1400	300	25	300	1–2.5		
Påkitsoq 4	1986	69°31′ N, 50°07′ W	320–440	1500	1100	38	40	>20	
Påkitsoq 5 (Lake 187)	1987	69°27.8′ N, 50°14.1′ W	200–220	485	465	40	5–20	?	
Påkitsoq 1	1985	69°25.9′ N, 50°16.0′ W	370–380	1226	870	666	2–5	>130	1
Påkitsoq 2	1988	69°25.9′ N, 50°16.0′ W	370–380	750	560	1450	0.5–1	>130	6
Påkitsoq 3	1992	69°25.9′ N, 50°16.0′ W	370–380	459.8	459.8	2299	0.2	>130	
Isunguata Sermia front	1987	67°11.3′ N, 50°19.2′ W	120–160	470	350	40	5–20	?	
Isunguata Sermia margin	1987	67°09.7′ N, 50°09.6′ W	450	540	360	152	1–10	?	
Næsset Kangerlussuaq	1987	67°09.2′ N, 50°01.5′ W	500	880	360	144	2–10	?	
Sermilik	1986	66°10.1′ N, 38°12.2′ W	?	?	0	10	?		
Nansen Halvø	1986	65° N, 41°30′ W	?	?	0	10	?		
Isortuarssup	1987	63°53′ N, 49°40′ W	925	590	450	40	10–20	?	

Sources: 1. Reeh and others (1987); 2. Oerter and others (1995); 3. Risbo and Pedersen (1994); 4. Reeh and others (1993); 5. Reeh and others (1990); 6. Reeh and others (1991).

Short records

Pleistocene ice is missing at 7 of the 15 $\delta^{18}O$ sampling sites: Hans Tausen Iskappe and Flade Isblink in eastern North Greenland, Tuto and Nuna Ice Ramps in northwest Greenland, Dronning Louise Land in central East Greenland, and Sermilik and Nansen Halvø in southeast Greenland. The missing Pleistocene ice at Tuto Ice Ramp and Hans Tausen Iskappe was discussed by Reeh and others (1990), Thomsen and others (1996) and Hammer and others (2001). These authors concluded that, most likely, Tuto Dome and Hans Tausen Iskappe did not survive the Holocene Climatic Optimum and thus are of middle- to late-Holocene origin. Very likely, a similar explanation applies to the other ice-margin sites listed above.

Long records

At the remaining ice-margin sampling sites, a band of pre-Holocene ice, 350–1700 m wide, occurs next to the ice edge (Fig. 4). As mentioned previously, a strong foliation (blue bands, thin dirt bands, light- and dark-appearing surface ice) characterizes the surface of the ice sampling sites (see Fig. 2). Starting from the ice edge, the following sequence of bands is typically observed (Reeh and others, 1987a):

(1) a moraine-free light-coloured band with relatively high $\delta^{18}O$ values, interpreted as composed of superimposed ice formed from local wind-drift winter snow accumulated along the ice edge;

(2) a moraine-covered band of blackish-appearing (extremely

Table 2. Early-Holocene and LGM mean $\delta^{18}O$ values measured on ice from Greenland ice margins

Site	$\delta^{18}O$ *Early Holocene* ‰	*LGM* ‰
Hans Tausen Iskappe A	−32.4 ± 0.2	n.a.
Hans Tausen Iskappe B	−31.4 ± 0.1	n.a.
Kilen, Flade Isblink	−19.3 ± 0.4	n.a.
Warming Land 1	n.a.	−45.0
Warming Land 2	n.a.	−45.5
Warming Land 3	−35.1 ± 0.7	−45.2
Warming Land 4	−36.3 ± 1.2	−45.5
Kronprins Christian Land K	−31.5 ± 0.1	−45.1 ± 0.2
Kronprins Christian Land KS		−45.2 ± 0.2
Inglefield Land	−25.6 ± 0.3	−36.5
Storstrømmen N	−35.8 ± 0.1	−42.8 ± 0.1
Storstrømmen NS	−36.1 ± 0.1	−43.2 ± 0.1
Nuna Ramp	−23.0 ± 0.1	n.a
Dronning Louise Land	−26.6 ± 0.2	n.a.
Tuto Ice Ramp	−19.1 ± 0.1	n.a.
Grandjean Fjord	−25.5	−37
Påkitsoq 4	−31.9 ± 0.3	−38.7
Påkitsoq 5 (Lake 187)	−32.5 ± 0.15	−39.5 ± 0.2
Påkitsoq 1	−32.8 ± 0.2	−39.6 ± 0.6
Påkitsoq 2	−32.5 ± 0.1	−39.7 ± 0.3
Påkitsoq 3	n.a.	−39.3 ± 0.1
Isunguata Sermia front	−28.3 ± 0.2	−33.8 ± 0.7
Isunguata Sermia marg	−28.0 ± 0.1	−33.9 ± 0.2
Næsset Kangerlussuaq	−28.0 ± 0.1	−33.0 ± 0.5
Sermilik	−16.2 ± 0.1	n.a.
Nansen Halvø	−12.7 ± 0.1	n.a.
Isortuarssup	−26.5 ± 0.1	−33.5

Note: n.a., not available.

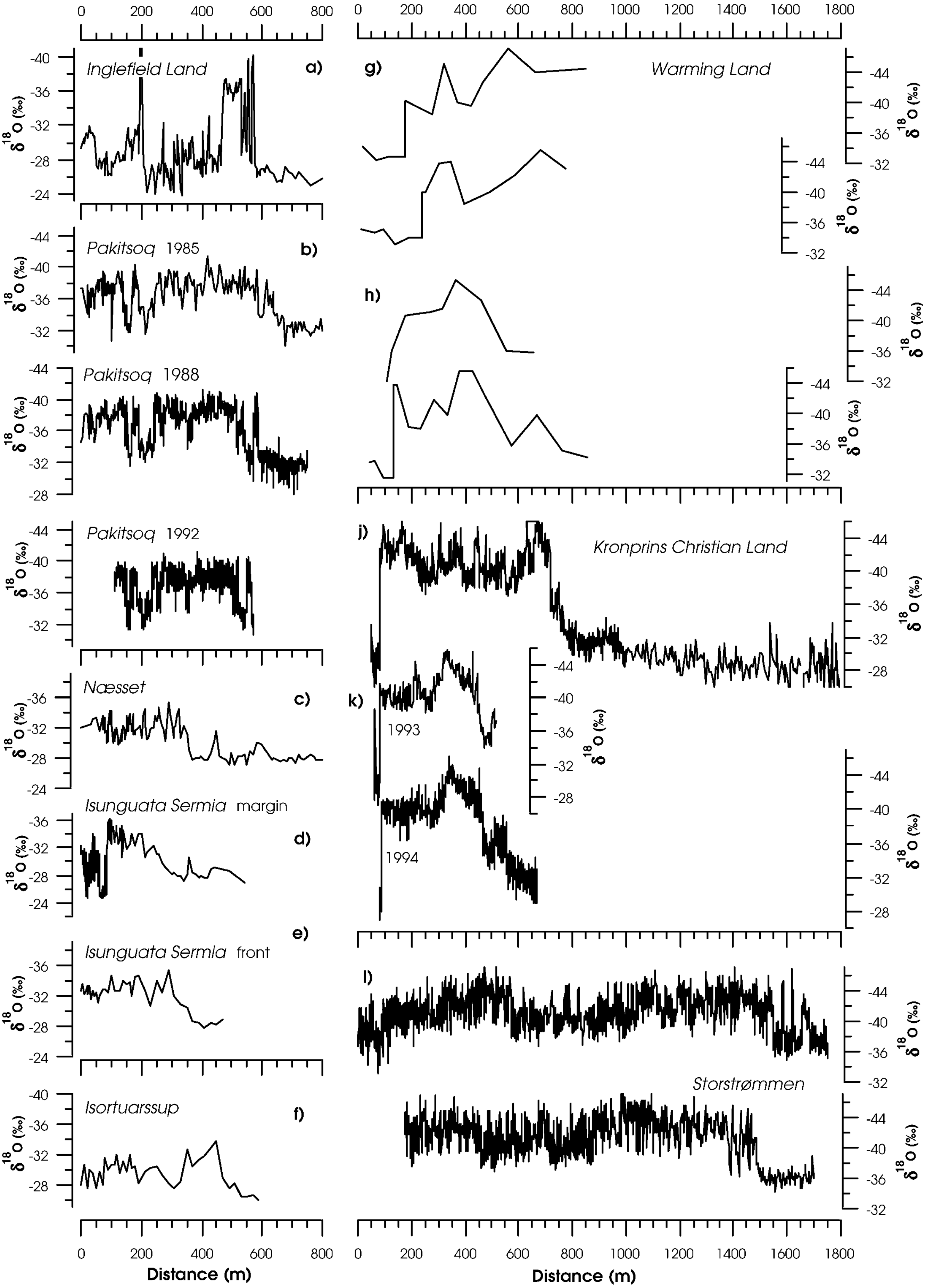

Fig. 4. $\delta^{18}O$ records from the Greenland ice-sheet margin dating back to the Pleistocene. For location, see map in Figure 3, and Table 1. References for the data are given in Table 1.

clear), isotopically homogeneous ice interpreted as regelation ice formed by freeze-on of meltwater at the glacier bed;

(3) a sequence of alternating light- and dark-appearing bands of bubbly glacier ice.

A general observation is that the light/dark-appearing ice correlates with high/low δ^{18}O values indicative of interglacial/glacial ice, respectively (Reeh and others, 1993). In some records, the superimposed-ice band and/or the regelation-ice band is missing.

Inglefield Land

The exact location of the Inglefield Land δ^{18}O profile is not known. Only scattered information about the sampling site is available. According to Risbo and Pedersen (1994), the outermost ~400 m of the profile (Fig. 4a) with highly variable δ^{18}O values (average ~−30‰) is from an ice ramp with numerous dust layers (debris layers?) and a strong foliation. The occurrence of moraine material of various sizes on the surface is suggestive of a shear zone in which material from the base is brought to the surface. The δ^{18}O values (average −36.5‰) of the section from 470 to 600 m indicate ice-age origin of this section, whereas the profile from 600 m onwards consists of Holocene ice.

Pâkitsoq

At Pâkitsoq, three complete profiles have been sampled for δ^{18}O analysis in August of 1985, 1988 and 1992 (Fig. 4b). In April 1994, a joint field programme was carried out with the aim of retrieving ice samples for studies of pollen, dust, chemistry, ice texture and fabric, and visual stratigraphy (Thomsen and Reeh, 1994). On this occasion, 300 samples for δ^{18}O analysis were collected in short sections distributed along the profile. The 1988 and 1992 profiles are displaced < 2.5 m apart, whereas the 1985 profile is located about 50 m north of the other profiles and strikes at a slightly different angle to the ice edge. A detailed description of the sampling site is given by Reeh and others (1994). Due to the difference in orientation of the profile lines, there is a small difference of the length scales along the profiles. Reeh and others (1991) showed that a close correspondence between the 1985 and 1988 profiles was obtained if distances along the 1985 profile were transferred to distances along the 1988 and 1992 profiles by following the strike of the foliation. With this adjustment, the three records are nearly identical, particularly considering the different sampling frequency (see Table 1).

Næsset Kangerlussuaq and Isunguata Sermia

The three δ^{18}O profiles shown in Figure 4c–e are sampled at locations some kilometres apart. The first profile (Fig. 4c) is from a stagnation zone with divergent flow. The outermost 80 m of the profile consists of moraine-covered regelation ice. Between 0 and 300 m, the surface has the dark appearance typical of glacial-period ice. From 300 m onwards the surface was of the light-coloured type with numerous cryoconite holes. The second profile (Fig. 4d) is from a steep side margin of a glacier lobe from the ice sheet a few kilometres to the north of the first sampling location. The outermost 70 m of the profile, with rapidly fluctuating δ^{18}O values, is a typical marginal shear zone with a dark-appearing surface due to abundant dirt bands and moraine material. The band is much darker, and different from the above-mentioned dark bands with ice from the glacial period. The abrupt jump of the δ^{18}O values to less fluctuating and lower values, interpreted as Wisconsinan ice, coincides with the boundary of the shear zone. The third profile (Fig. 4e) is from the front of the glacier lobe. This profile begins at some distance from the terminus of the lobe. The surface along the entire profile consists of bubbly glacier ice. The colour of the surface ice as well as the δ^{18}O signature suggests that the Pleistocene–Holocene transition is located around 400 m.

Isortuarssup

The δ^{18}O profile from Isortuarssup at the margin of the Greenland ice sheet is shown in Figure 4f. Detailed information about the sampling site is not available.

Warming Land

The δ^{18}O records from Warming Land shown in Figure 4g and h were sampled at two locations ~30 km apart (Reeh and others, 1987a). The relatively high δ^{18}O values between −30‰ and −35‰ in the outermost 100–250 m of the profiles most likely represent superimposed ice formed from local wind-drift winter snow. Apparently, the Pleistocene–Holocene transition is present only in the profiles shown in Figure 4h, where it is located 470–550 m from the ice edge. The large sample spacing (see Table 1) prevents further interpretation of the profiles.

Kronprins Christian Land

The δ^{18}O profile shown in Figure 4j (profile K) and the two profiles shown in Figure 4k (profile KS) are sampled from ice-margin locations ~5 km apart. A description of the sampling sites is given by Oerter and others (1995). The profiles from the different sites do not correlate very well. It is likely that profile K is disturbed by large-scale folding, as the section from 80 to 400 m looks like the mirror image of the section from 400 to 700 m. A large-scale elliptically shaped closed-banded structure visible on aerial photos of the ice surface supports this hypothesis. The transition from Pleistocene ice to Holocene ice is evident in both profiles. It correlates well with a colour change of the surface ice from dark-appearing Pleistocene ice to lighter-coloured Holocene ice. Neither of the records extends back to the previous interglacial period, in contrast to the detailed δ^{18}O records from Pâkitsoq, central West Greenland. The high δ^{18}O values at the beginning of the profiles originate from a marginal shear zone.

Storstrømmen

The two δ^{18}O profiles shown in Figure 4l (profile N above, profile NS below) were sampled along two parallel lines approximately 500 m apart. A detailed description of the sampling site is given by Reeh and others (1993), who also showed that a good correspondence between the main part of the two profiles is established by following the large-scale surface foliation as represented by major blue bands from one profile to the other. Neither of the records extends back into the previous interglacial period. However, judging by the δ^{18}O variations, the records are longer than those obtained from Kronprins Christian Land.

CORRELATION WITH ICE-CORE RECORDS

An attempt to correlate the ice-margin δ^{18}O records from Pâkitsoq and Storstrømmen with deep ice-core records was made by Reeh and others (1991, 1993). Based on the correlations, a chronology was established for the ice-margin records by using the ice-core time-scale. The suggested correlation, based on comparison of characteristic δ^{18}O events in the ice-

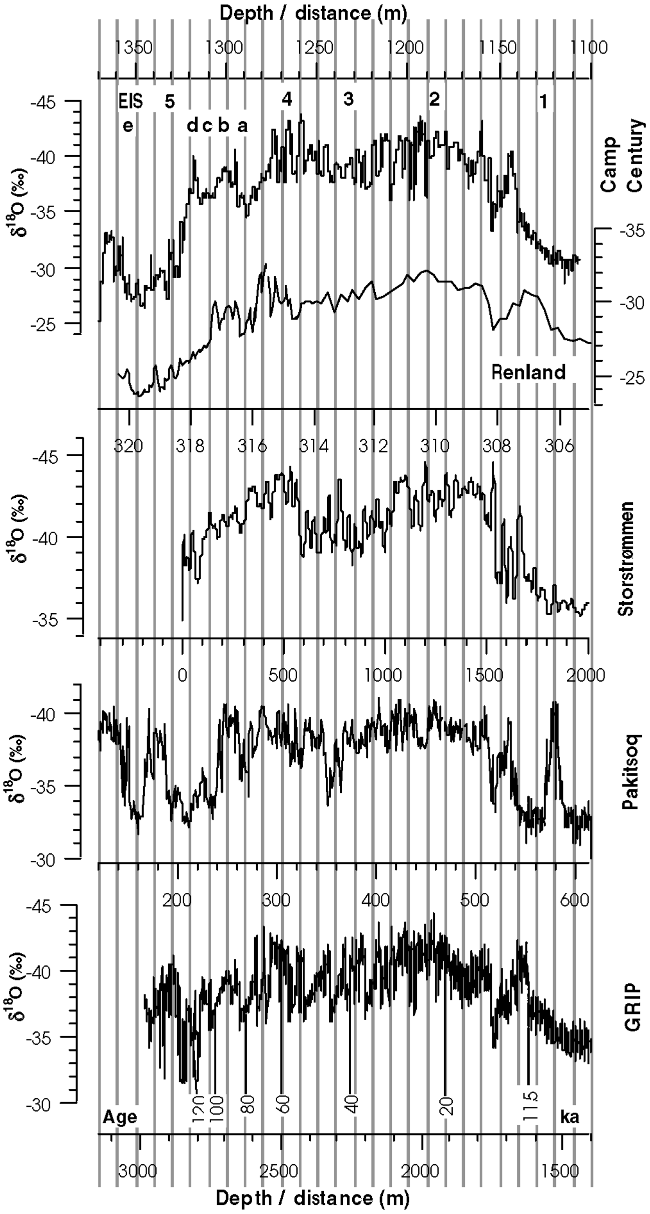

Fig. 5. Comparison of ice-margin $\delta^{18}O$ records from Storstrømmen (running means over 12 samples of profile N) and Pâkitsoq (1988 profile) with ice-core $\delta^{18}O$ records from Camp Century and Renland (Johnsen and others, 1992a) and GRIP Summit (Dansgaard and others, 1993). Emiliani isotopic stages (EIS) are shown at the top of the figure. Ages along the Camp Century and Summit $\delta^{18}O$ records are from Johnsen and others (1992a) and Dansgaard and others (1993).

margin and ice-core records, still holds. However, the chronology previously suggested by Reeh and others (1991, 1993) must be revised. This chronology relied heavily on a single high value in the ^{10}Be-concentration profile measured on ice from the Camp Century deep ice core (Beer and others, 1988). An age of 60 kyr was assigned to this peak by correlation with a similar peak in the ^{10}Be record from the Vostok deep ice core in Antarctica. Later studies (Beer and others, 1992) and evidence from the Greenland Icecore Project (GRIP) ice-core record showed this interpretation to be wrong. In Figure 5, showing the δ^{18}O records from Camp Century, Renland, GRIP Summit, Pâkitsoq and Storstrømmen, a revised chronology for the Pâkitsoq and Storstrømmen δ^{18}O records is indicated. The section of the Pâkitsoq profile from 150 to 240 m, previously interpreted as Emiliani's isotopic stage 5a–5e (EIS5a–e) is now interpreted as covering only the last interglacial (the Eemian, EIS5e). Moreover, the isolated peak at 580 m in the 1988 Pâkitsoq record (also present in the 1992 record), previously interpreted as the Younger Dryas cold spell at the end of the last ice age, is probably an artefact reflecting a major disturbance of the record caused by large-scale folding of layers of glacial/interglacial ice of different competence (Dahl-Jensen, 1985). It is more likely that the Younger Dryas is represented by the δ^{18}O peak at 530 m.

The previous interpretation by Reeh and others (1993) assigned an age of ~80 kyr to the oldest ice in the Storstrømmen record. Using the revised time-scale, this age is changed to ~110 kyr. However, it is obvious that ice from the Eemian is not found in the Storstrømmen record. The relatively high δ^{18}O values in EIS3 in the Storstrømmen record may indicate a more pronounced warming in northern East Greenland in EIS3 than in other regions of Greenland.

FLOWLINE MODELLING

A flowline model, essentially similar to the model presented by Reeh (1988) and Reeh and Paterson (1988), is used to determine the locations on the ice sheet where 11.5 and 20 kyr old ice in the ice-margin records was originally deposited as snow. These ages correspond approximately to the Pleistocene–Holocene transition and the late-Wisconsinan maximum, respectively (Johnsen and others, 1992b).

The flowline model is a steady-state model using the present Greenland surface and base elevations, mass balance and temperature distribution as input. First, the course of the flowlines terminating at the sampling sites for the long ice-margin δ^{18}O records is determined as trajectories to the ice-sheet sur-

Table 3. Comparison of early-Holocene (EH) and LGM $\delta^{18}O$ values measured on ice from Greenland ice margins (IMR) with the present surface values at the model-calculated sites of snow deposition (Map)

Site	*Site of deposition of 20 kyr old ice*	*EH $\delta^{18}O$*		*LGM $\delta^{18}O$*		*EH – LGM $\delta^{18}O$*	*EH – LGM $\delta^{18}O$*	
		IMR	*Map**	*IMR*	*Map**	*IMR*	*Map**	*Corrected*
		‰	‰	‰	‰	‰	‰	‰
Warming Land	79°52′ N, 48°59′ W	−35.4 ± 0.7	−33.7	−45.3	−34.4	0.7	9.9 ± 1.2	9.2 ± 1.4
Kronprins Christian Land	79°38′ N, 37°46′ W	−31.5 ± 0.1	−32.6	−43.3 ± 0.2	−34.2	1.6	11.8 ± 0.2	10.2 ± 0.8
Inglefield Land		−25.6 ± 0.3	n.a.	−36.5	n.a.		10.9 ± 1.1	
Storstrømmen	75°13′ N, 33°35′ W	−36.0 ± 0.1	−35.9	−43.0 ± 0.1	−36.2	0.3	7.0 ± 0.15	6.7 ± 0.2
Pâkitsoq	71°06′ N, 38°41′ W	−32.5 ± 0.1	−32.6	−39.6 ± 0.2	−33.6	1.0	7.1 ± 0.2	6.1 ± 0.6
Næsset/Isunguata Sermia	66°55′ N, 43°07′ W	−28.0 ± 0.1	−28.2	−33.8 ± 0.2	−28.1	−0.1	5.8 ± 0.2	5.9 ± 0.2
Isortuarssup	63°08′ N, 44°57′ W	−26.5 ± 0.1	−27.1	−33.5	−27.1	0.0	7.0 ± 1.0	7.0 ± 1.0

* Standard error of the map values is put equal to the rms value (0.45‰) of the residuals between measured δ^{18}O values and corresponding map values.

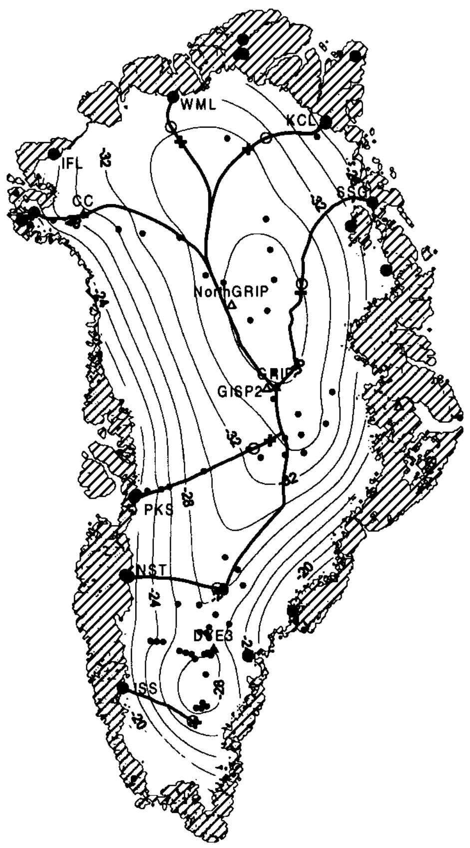

Fig. 6. Present distribution of mean annual $\delta^{18}O$ of precipitation on the Greenland ice sheet illustrated by isolines (thin lines) with location of data points indicated by small dots. Large dots are ice-margin $\delta^{18}O$ sampling locations. Heavy lines are flowlines to these locations. Open circles and crosses are sites of origin of 11.5 and 20 kyr old ice in the ice-margin $\delta^{18}O$ records, as determined by ice-dynamics flowline calculations. Open triangles are deep ice-core drilling sites.

face elevation contours. Next, the flow in vertical sections along these flowlines is modelled. The divergence/convergence along the flowlines is expressed in terms of the curvature of the surface elevation contours at their intersection with the flowlines. The model accounts for the depth distributions of temperature and normal stress deviators, and possible enhanced flow in a bottom layer of ice of Wisconsinan origin (Paterson, 1994, p. 282). The ice-velocity distribution in the vertical sections is calculated with due account also taken of ice-thickness variations. Finally, steady-state particle paths and travel times of ice particles from the deposition site in the accumulation zone to the site of resurfacing in the ablation zone are calculated. For further details of the model, the reader is referred to Reeh (1988).

On the map in Figure 6, the flowlines terminating at the ice-margin sampling locations for the "long records" are displayed as thick lines. A flowline calculation has not been performed for the Inglefield Land location because the accurate sampling site is unknown. For the other locations, the model-calculated deposition sites of 11.5 and 20 kyr old ice are shown in the map as open circles and crosses, respectively.

The present distribution of $\delta^{18}O$ in the surface snow in Greenland is also illustrated in Figure 6 by isolines. The isolines are determined by gridding and contouring the scattered $\delta^{18}O$ values measured on Greenland precipitation, i.e. surface snow from the ice sheet or local glaciers, and mean annual precipitation collected at coastal weather stations. The sampling sites are shown as black dots in Figure 6.

In Table 3, the measured early-Holocene mean $\delta^{18}O$ values of the ice-margin records are listed together with the present surface $\delta^{18}O$ values at the locations where the snow, according to the ice-flow modelling, was originally deposited ~11.5 kyr ago. Moreover, the measured LGM $\delta^{18}O$ values of the ice-margin records are listed together with the present surface $\delta^{18}O$ values at the locations where the snow, according to the ice-flow modelling, was originally deposited ~20 kyr ago. The last two columns of the table show the LGM to Holocene $\delta^{18}O$ change as determined directly from the ice-margin records, and the same $\delta^{18}O$ change corrected with the difference between the present surface $\delta^{18}O$ values at the 11.5 and 20 kyr model-calculated deposition sites.

DISCUSSION AND CONCLUSIONS

Ideally, the differences shown in Table 3 between measured (IMR) and "calculated" (Map) $\delta^{18}O$ values should reflect the differences between the $\delta^{18}O$ values of surface snow deposited, respectively, 11.5 and 20 kyr ago and present $\delta^{18}O$ values. However, errors of the $\delta^{18}O$ contour map and errors of the flowline model must be taken into account.

As to the errors of the $\delta^{18}O$ contour map, the root-mean-square (rms) value of the residuals between the measured mean annual $\delta^{18}O$ values and the map values is 0.45‰. Due to the irregular distribution of the data points, there is a considerable geographic variation of the accuracy of the surface $\delta^{18}O$ map. The discrepancy between the early-Holocene IMR and Map values of the Warming Land and Kronprins Christian Land records can very likely be referred to errors of the $\delta^{18}O$ map, as very few $\delta^{18}O$ measurements are available in the relevant regions of the ice sheet.

As to the errors of the flowline model, it may, at first glance, seem to make little sense to use a steady-state flow model to calculate the particle path and travel time from the site of snow deposition to the ice margin. Since 11.5 kyr ago, the geometry and flow pattern of the ice-sheet margin has experienced large changes. However, as discussed by Reeh and others (1987b), the consequences of even rather dramatic ice-margin fluctuations may not be so serious: 11.5 kyr old ice at the surface near the ice edge was, during the first many thousand years of its motion towards the margin, located in a region of the ice sheet where geometry (ice thickness) was not much different from present-day geometry (Letréguilly and others, 1991). It is therefore acceptable to apply present-day ice-sheet geometry to model the particle paths since 11.5 kyr ago, or even since 20 kyr ago. But travel times must be adjusted to account for changes of mass balance. Since 11.5 kyr ago, accumulation rates on the Greenland ice sheet have not changed very much, and assuming constant accumulation rates equal to present values seems to be acceptable. Actually, the close agreement between the IMP and Map $\delta^{18}O$ values in regions where the $\delta^{18}O$ map is well constrained by measured values (i.e. upstream of Storstrømmen, Pâkitsoq and Næsset/Isunguata Sermia; see map in Fig. 6) suggests that our ice-flow model performs well at least back to 11.5 kyr ago.

Between 11.5 and 20 kyr ago, accumulation rates in Greenland were less than half their present values (Dahl-Jensen and others, 1993). Consequently, the deposition site of 20 kyr old ice is located closer to the 11.5 kyr deposition site than predicted by our flow model, which uses a constant accumulation rate equal to the present value also for the period 11.5–20 kyr ago. The deposition site is also influenced by temporal changes of ice flow due to changing ice temperature and flow properties, complications that have also been neglected in our modelling. The correction term to the Pleistocene–Holocene δ^{18}O shift due to different deposition sites of 11.5 and 20 kyr old ice listed in Table 3 is an upper limit, and the real δ^{18}O shift is somewhere between the values listed in the last two columns of Table 3. Thus, the δ^{18}O shift at the end of the Last Glacial was ~10‰ in North Greenland, and 6–7‰ in central and southern Greenland, in agreement with values of the Pleistocene–Holocene δ^{18}O change measured on deep ice cores in Greenland (see Table 4, after Paterson (1994, table 15.2)). Paterson (1994) estimates the uncertainty of the ice-core derived changes to ±1‰. Based on Tables 3 and 4, we conclude that, south of ~75° N, i.e. on the main part of the Greenland ice sheet, the Pleistocene–Holocene δ^{18}O shift was rather uniform at 6–7‰. North of ~77° N the shift is ~10‰. It is worth noting that, in all ice-margin and ice-core records with a 6–7‰ δ^{18}O shift, the ice from the Pleistocene–Holocene transition originates near the main Greenland ice divide. In contrast, in all records with a ~10‰ δ^{18}O shift, ice from the transition has its origin at the north-facing slope of the Greenland ice sheet (see map in Fig. 6). Camp Century, with a large δ^{18}O shift, is indeed located near a local ice divide, but in broad outline the location must be characterized as a slope location.

Different changes of the environment may contribute to a shift in δ^{18}O: (1) a climatic temperature change at the deposition site; (2) a surface-elevation change at the deposition site; (3) a change of the vapour source region; (4) a change of the seasonal distribution of the precipitation.

Ice-core and borehole studies at GRIP Summit (Dahl-Jensen and others, 1998) show that the Pleistocene–Holocene δ^{18}O shift of 7‰ at this location corresponds to a temperature change on the order of 20 K. By analogy, the 10‰ δ^{18}O shift on the northern slope should then correspond to a temperature change of ~30 K, if the 10‰ δ^{18}O shift was solely caused by a climatic temperature change. On the other hand, using the present δ^{18}O–elevation relationship in Greenland of ~0.7‰ δ^{18}O per 100 m elevation change, the 3.5‰ excess δ^{18}O shift on the north-facing slopes of the ice sheet could be explained by a ~500 m increase of surface elevation during the LGM as compared to the present. It is possible that the excess δ^{18}O change on the north-facing slopes of Greenland is caused by a change of the vapour source for the snow precipitation due to a change of the atmospheric general circulation pattern between the LGM and now. General circulation model experiments by G. Krinner and others (unpublished information) show changes of precipitation seasonality between the LGM and now, large enough to account for a δ^{18}O shift of several per mil. Also, the "cyclone mechanism" (Holdsworth, 2001) offers an explanation of markedly different Pleistocene–Holocene δ^{18}O shifts within the same region.

Which explanation or combination of explanations is correct cannot be resolved by this study. However, our study shows that the much-debated North Greenland δ^{18}O anomaly known from the Camp Century deep ice-core record (e.g. Johnsen and others, 1992a) is a general feature for the north-facing slope of Greenland, and that an explanation must therefore involve the entire northern slope of the Greenland ice sheet.

The different time-span covered by the ice-margin δ^{18}O records is also worthy of discussion. As illustrated in Figures 4 and 5, Pâkitsoq is the only ice-margin location where ice interpreted to be of pre-Eemian origin has been found. That Eemian and probably also Pre-Eemian ice is preserved in central Greenland is confirmed by the ice-core records from GRIP and Greenland Ice Sheet Project 2 (GISP2) from near the deposition site of the old ice in the Pâkitsoq record (see map in Fig. 6). The missing Eemian ice in the Storstrømmen ice-margin record, and the probably even shorter record from Kronprins Christian Land (see Fig. 4), might indicate that significant bottom melting is taking place or has taken place sometime in the past somewhere along the flowlines leading to these sampling sites. Another explanation might be that the northeast sector of the ice sheet was greatly reduced during the warm Eemian interglacial and that the later build-up of the ice sheet was mainly by local snow deposition and not by ice flow from the Summit region. Such a scenario with a significant reduction of the northeast Greenland ice-sheet sector in the Eemian interglacial is supported by a time-dependent thermomechanical model study of the Greenland ice sheet forced by a glacial–interglacial climate cycle (e.g. Letréguilly and others, 1991). Radiocarbon-dated reworked marine organic material also suggests a significant retreat of the northeast Greenland ice-sheet margin 32–37 kyr ago (Weidick and others, 1996; Landvik and others, 2001).

Our results show that δ^{18}O records from the Greenland ice-sheet margin provide useful information about climate and dynamics of the ice sheet, and thus are important (and cheap) supplements to deep ice-core records. There are still large regions that have not been covered by ice-margin δ^{18}O records (see map in Fig. 3).

To be useful, ice-margin δ^{18}O profiles should be sampled in some detail, i.e. with 1–2 m sample distance. As the width of the band of pre-Holocene ice at the hitherto sampled locations is 300–1700 m, this means that the number of samples to be collected at each location is on the order of 1000. Until now, a rather primitive sampling procedure has been applied. It might be worth developing a more sophisticated method aimed at cutting what could be termed a horizontal core from the surface of the ice margin. This would allow the establishment of continuous records, and also allow measurement of constituents other than δ^{18}O on the margin ice (Thomsen and Reeh, 1994).

ACKNOWLEDGEMENTS

We wish to thank all those who have spent time collecting ice samples from ice margins in Greenland, while visiting these remote areas for other purposes. The research was supported by the Commission of the European Communities under contracts EPOC-CT90-0015 and ENV4-CT95-0124, by the Nordic Council of Ministers Environmental Research Programme, by the Commission for Scientific Research in Greenland, and by the Danish Natural Sciences Research Council. The research on GEUS (Geological Survey of Denmark and Greenland) material is published with the permission of the Geological Survey of Denmark and Greenland. Comments by G. Holdsworth and an unknown reviewer led to improvements of the paper.

REFERENCES

Beer, J. *and 6 others*. 1988. Information on past solar activity and geomagnetism from ^{10}Be in the Camp Century ice core. *Nature*, **331**(6158), 675–679.

Beer, J. *and 8 others*. 1992. ^{10}Be peaks as time markers in polar ice cores. *In* Bard, E. and W. S. Broecker, *eds. The last deglaciation: absolute and radiocarbon chronologies*. Berlin, etc., Springer-Verlag, 141–153. (NATO ASI Series I: Global Environmental Change 2.)

Dahl-Jensen, D. 1985. Determination of the flow properties at Dye 3, south Greenland, by bore-hole-tilting measurements and perturbation modelling. *J. Glaciol.*, **31**(108), 92–98.

Dahl-Jensen, D., S. J. Johnsen, C. U. Hammer, H. B. Clausen and J. Jouzel. 1993. Past accumulation rates derived from observed annual layers in the GRIP ice core from Summit, central Greenland. *In* Peltier, W. R., *ed. Ice in the climate system*. Berlin, etc., Springer-Verlag, 517–532. (NATO ASI Series I: Global Environmental Change 12.)

Dansgaard, W. *and 6 others*. 1982. A new Greenland deep ice core. *Science*, **218**(4579), 1273–1277.

Dansgaard, W. *and 10 others*. 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, **364**(6434), 218–220.

Hammer, C. U., S. J. Johnsen, H. B. Clausen, D. Dahl-Jensen, N. Gundestrup and J. P. Steffensen. 2001. The paleoclimate record from a 345 m long ice core from the Hans Tausen Iskappe. *Medd. Grønl., Geoscience* 39, 87–95.

Holdsworth, G. 2001. Calibration changes in the isotopic thermometer for snow according to different climatic states. *Geophys. Res. Lett.*, **28**(13), 2625–2628.

Johnsen, S. J. *and 7 others*. 1992a. A "deep" ice core from East Greenland. *Medd. Grønl., Geoscience* 29.

Johnsen, S. J. *and 9 others*. 1992b. Irregular glacial interstadials recorded in a new Greenland ice core. *Nature*, **359**(6393), 311–313.

Jouzel, J. *and 6 others*. 1987. Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). *Nature*, **329**(6138), 403–408.

Lanvik, J. Y., A. Weidick and A. Hansen. 2001. The glacial history of the Hans Tausen Iskappe and the last glaciation of Peary Land, North Greenland. *Medd. Grønl., Geoscience* 39, 27–44.

Letréguilly, A., N. Reeh and P. Huybrechts. 1991. The Greenland ice sheet through the last glacial–interglacial cycle. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **90**(4), 385–394.

Lorius, C. and L. Merlivat. 1977. Distribution of mean surface stable isotope values in East Antarctica: observed changes with depth in the coastal area. *International Association of Hydrological Sciences Publication* 118 (Symposium at Grenoble 1975 — *Isotopes and Impurities in Snow and Ice*), 127–137.

Lorius, C. *and 6 others*. 1985. A 150,000-year climatic record from Antarctic ice. *Nature*, **316**(6029), 591–596.

Oerter, H., C. E. Bøggild, F. Jung-Rothenhäusler and N. Reeh. 1995. AWI contribution to final report on Climate and Sea Level Change and the Implications for Europe, EU Environment 1990–94. *In Climate and sea level change and the implications for Europe. Appendix A*. Brussels, Commission of the European Communities. Directorate-General for Science, Research and Development. Environment Programme. (Final report. Contract EV5V-CT91-0051, DGXII.)

Paterson, W. S. B. 1994. *The physics of glaciers. Third edition*. Oxford, etc., Elsevier.

Raynaud, D. 1977. *Les inclusions gazeuses dans la glace de glacier: leur utilisation comme indicateur du site de formation de la glace polaire; application climatiques et rhéologiques*. Grenoble, Centre National de la Recherche Scientifique. Laboratoire de Glaciologie. (Publication 214.)

Reeh, N. 1988. A flow-line model for calculating the surface profile and the velocity, strain-rate, and stress fields in an ice sheet. *J. Glaciol.*, **34**(116), 46–54.

Reeh, N. and W. S. B. Paterson. 1988. Application of a flow model to the ice-divide region of Devon Island Ice Cap, Canada. *J. Glaciol.*, **34**(116), 55–63.

Reeh, N., H. H. Thomsen and H. B. Clausen. 1987a. The Greenland ice sheet margin — a mine for paleo-environmental studies. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **58**(2), 229–234.

Reeh, N., C. U. Hammer, H. H. Thomsen and D. A. Fisher. 1987b. Use of trace constituents to test flow models for ice sheets and ice caps. *International Association of Hydrological Sciences Publication* 170 (Symposium at Vancouver 1987 — *The Physical Basis of Ice Sheet Modelling*), 299–310.

Reeh, N., H. H. Thomsen, P. Frich and H. B. Clausen. 1990. Stable isotope studies on ice margins in the Thule area. *Medd. Grønl., Geoscience* 22, 47–56.

Reeh, N., H. Oerter, A. Letréguilly, H. Miller and H.-W. Huberten. 1991. A new, detailed ice-age oxygen-18 record from the ice-sheet margin in central West Greenland. *Palaeogeogr., Palaeoclimatol., Palaeoecol., Global Planet. Change Sect.*, **90**(4), 373–383.

Reeh, N., H. Oerter and H. Miller. 1993. Correlation of Greenland ice-core and ice-margin $\delta(^{18}O)$ records. *In* Peltier, W. R., *ed. Ice in the climate system*. Berlin, etc., Springer-Verlag, 481–497. (NATO ASI Series I: Global Environmental Change 12.)

Reeh, N., H. H. Thomsen, H. Oerter and C. E. Bøggild. 1994. Surface topography, ice ablation, ice deformation and velocities along the Paakitsoq profile sampling line. *Grønl. Geol. Undersøgelse, Open File Series* 94/15, 20–29.

Risbo, T. and H. Pedersen. 1994. Kap York-meteoritekspeditionen. *In Carlsbergfondet Frederiksborgmuseet Ny Carlsbergfondet Årsskrift*. Copenhagen, RHODOS Internationalt Forlag for Videnskab og Kunst, 38–45.

Thomsen, H. H. and N. Reeh, *eds*. 1994. Field report of paleo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland. *Grønl. Geol. Undersøgelse, Open File Series* 94/15.

Thomsen, H. H., N. Reeh, O. B. Olesen and P. Jonsson. 1996. Glacier and climate research on Hans Tausen Iskappe, North Greenland: 1995 glacier basin activities and preliminary results. *Grønl. Geol. Undersøgelse* 172, 78–84.

Weidick, A., C. Andreasen, H. Oerter and N. Reeh. 1996. Neoglacial glacial changes around Storstrømmen, north-east Greenland. *Polarforschung*, **64**(3), 1994, 95–108.