High Deglaciation Rates in Denmark During the Late Weichselian – Implications for the Palaeoenvironment

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Available geologic evidence suggests that the mean deglaciation rate in Denmark 18,000-17,000 calendar years BP was at least about 100 m/year, probably requiring a total vertical ice ablation of 30-35 m/year. This ablation value is large when compared to the amount of ice ablation that could be expected on physical grounds. The reasons for this apparent discrepancy are discussed and factors such as glacier bed strength characteristics, presence of marginal water bodies and occurrence of strong catabatic winds are suggested as environmental phenomena that should be taken into consideration when formulating dynamic deglaciation models and reconstructing the Late Weichselian palaeoenvironment in Denmark; climate alone does not explain the observed patterns and rates of deglaciation.

Keywords: *Late Weichselian, deglaciation, ablation, Denmark*

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The causes for the growth and collapse of the large Pleistocene ice sheets are topics of intense scientific debate, and the amount of new data and ideas has been large during the last twenty years. Significant progress has also been made in the modelling of land ice masses as well as in the understanding of the role they play in the climate system, and vice versa (see, e.g. Manabe and Broccoli 1985). However, especially concerning the deglaciation period, the amount of new stratigraphic information such as datings has been substantial, and deglaciation isochrone maps have been published both for the Weichselian North European Ice Sheet and the Wisconsin Laurentide North American Ice Sheet (see, e.g. Andrews 1973, Berglund 1979, Lagerlund et al. 1983, Boulton et al. 1985, Dyke and Prest 1987, Lagerlund and Houmark-Nielsen 1993). In what follows, published conventional ^{14}C ages have been corrected according to the results obtained by Bard et al. (1990, 1993) from studies on corals. This is important for ages higher than 9 ka BP (^{14}C years), which must be corrected toward higher ages. The correction factor is about 1 ka at "old" ^{14}C ages of about 10 ka BP, increasing to 3.5 ka for "old" ^{14}C ages of about 20 ka BP. Figure 2 illustrates the ^{14}C-year to calendar-year conversion for the Late Weichselian in Denmark. In what follows, ages will be given as calendar years.

The stream of new information on Late Weichselian deglaciation has resulted in several important analyses and discussions on the palaeoenvironment during the general deglaciation period from 22 ka BP to 8 ka BP (e.g. Andrews and Barry 1978, Berthelsen 1979, Berglund 1979, Lagerlund et al. 1983, Boulton et al. 1985, Dyke and Prest 1987, Houmark-Nielsen 1987, Lidmar-Bergström et al. 1991, Lagerlund and Houmark-Nielsen 1993). One common denominator, however, emerges from the steady flow of new data: both in North America and in Northern Europe the associated frontal ice-recessional rates were surprisingly high during this period; at least when compared to rates observed at modern glaciers. Several years ago Andrews (1973) drew attention to this problem for the Wisconsin Laurentide Ice Sheet, and it is the purpose of the present paper to look into the analogue situation for the SW-part of Scandinavia during the Weichselian deglaciation. In the present paper we concentrate on Late Weichselian deglaciation rates and the different mechanisms that might have caused the rather rapid collapse of the Danish sector of the Weichselian ice sheet. The analysis will be attempted by applying the improved possibility of obtaining numeric 3D-reconstructions on the surface form of former ice sheets, given their former margins and the physical character of the substratum. Also results obtained from insolation calculations as well as empirical knowledge on ablation rates from modern glacier surfaces obtained from proper mass balance measurements will be used.

Late Weichselian Deglaciation of Denmark

From a palaeo-glaciological point of view, the Danish sector of the Weichselian North European Ice Sheet was dynamically complex. This was the case because a southerly flow of ice from Norway here coalesced with ice masses nourished by vast accumulation areas northeast and east of Denmark, over the central part of Scandinavia and the Baltic. Furthermore, during most of the Weichselian the Danish area was probably close to the contemporary sea level. In the Late Weichselian the ice sheet came

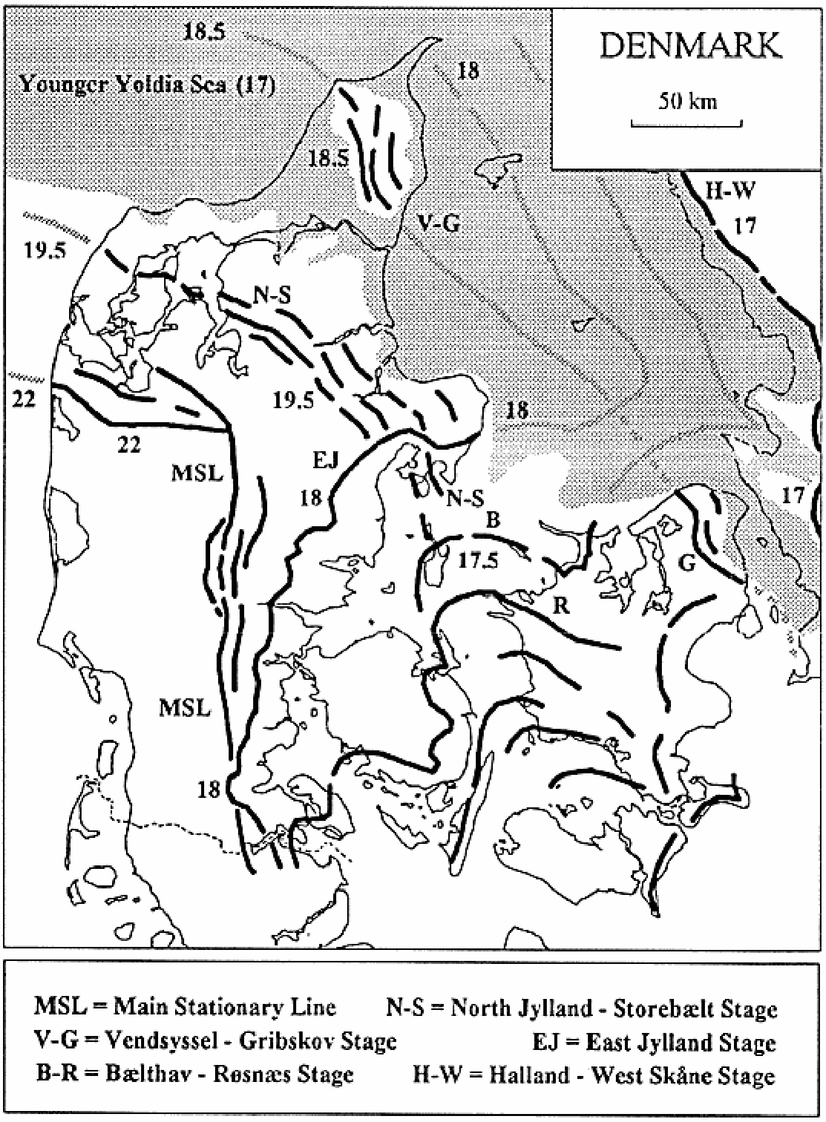

Fig.1. Main features of the Weichselian deglaciation of Denmark. Compiled from Berglund (1979), Lagerlund et al. (1983), Houmark-Nielsen (1987), Smed (1992) and Lagerlund and Houmark-Nielsen (1993). Published ^{14}C ages have been corrected according to Bard et al. (1990, 1993) and are given in calendar years.

in direct contact with the ocean within the area from time to time (Lagerlund and Houmark-Nielsen 1993). The climate must have undergone large variations, being cold-arid at times when the extension of the ice sheet prevented the ocean from having access to the Danish area, and cold-maritime at times when the ocean had access to the area. Naturally, the overall mass balance characteristics of the Danish ice sheet sector must have changed according to this.

An outline of the main features of the Late Weichselian deglaciation of Denmark is shown in Fig.1, compiled from various sources (Mangerud and Berglund 1978, Berglund 1979, Lagerlund et al. 1983, Lagerlund 1987, Houmark-Nielsen and Lagerlund 1987, Ringberg 1988, Houmark-Nielsen 1987, Lidmar-Bergström et al. 1991, Smed 1992, Lagerlund and Houmark-Nielsen 1993). The conversion from conventional ^{14}C years to calendar years is shown in Figure 2. Around 22 ka BP global sea level was near its eustatic minimum, and off the North European seaboard, the shoreline was probably 110-120 m below present sea level on the outer shelf (Clarck and Kingle 1979, Kjemperud 1986). At this time the North European Ice Sheet achieved its overall maximum size, having its south-western margin standing along the Main Stationary Line (MSL) in central Jutland, Denmark (Fig.1). From 22 ka BP the ice sheet melted back, although interrupted by several important readvances, and shortly before 17 ka BP the last active ice lost contact with the present south-

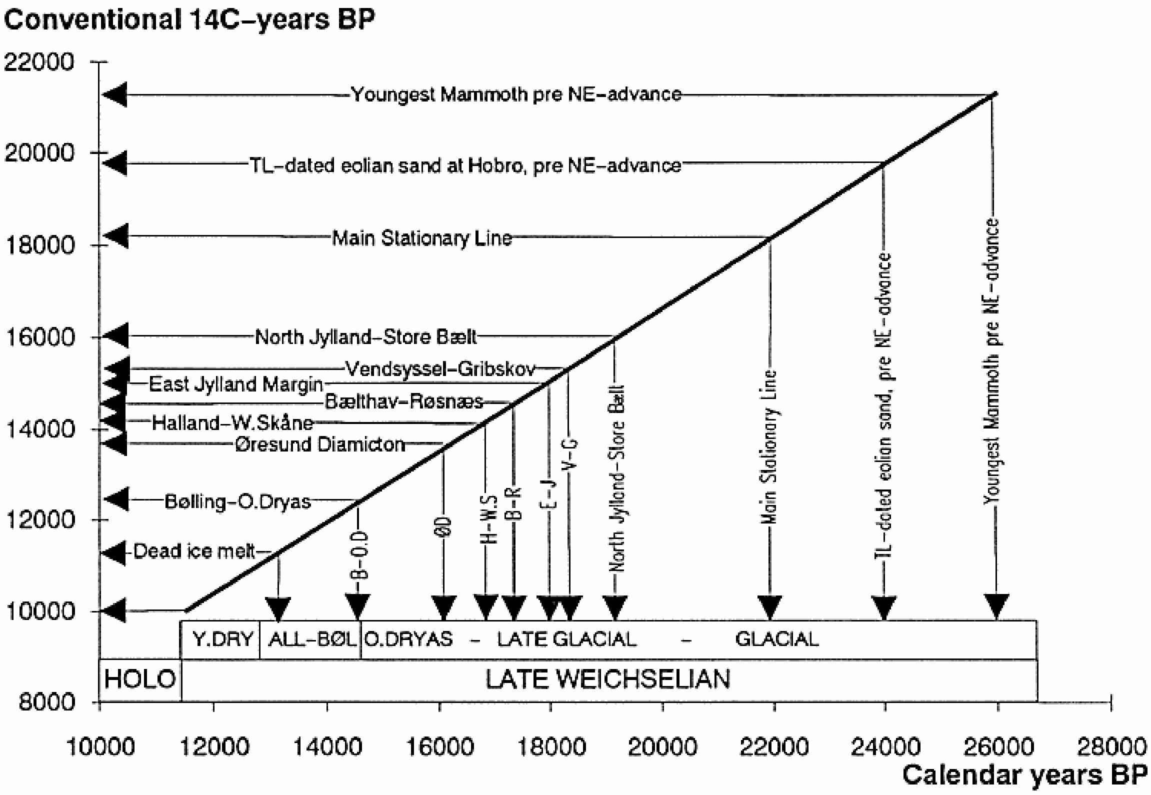

Fig.2. Conversion from conventional 14C ages to calendar years for selected events during the Danish Late Weichselian.

eastern Denmark. The geomorphology of Denmark indicates that stagnated ice masses were detached from the ice sheet during the deglaciation at many localities, while the ice sheet melted back by way of frontal deglaciation at other localities.

During the early part of the Late Weichselian, the ice sheet melted back towards north and east (Fig.1). This pattern was, however, interrupted shortly after 18.5 ka BP. A major readvance from the east and southeast now again brought active ice close to the Main Stationary Line in southern and central Jutland at 18 ka BP (EJ, Fig.1). This overall maximum position was even overridden a few places in southern Jutland.

At the time of this major Baltic readvance (18 ka BP), the Norwegian ice no longer had contact with the present Danish land area, probably due to calving induced by the rising global sea level, and the ocean now covered the northern part of present Denmark, and was in contact with the ice sheet margin in the southern part of the present Kattegat Sea area. This ocean extension is known as the Younger Yoldia Sea. It transgressed northern Jutland slightly before 18.5 ka BP, and had its maximum extension around 16.5 ka BP. The present Swedish west coast was transgressed around 17 ka BP (Fig.1). Without any doubt, this significant geographical change was associated with environmental changes also, probably in the direction of a warmer and certainly moister summer climate. This assumed environmental change may be the climatic background for the following activity of the Baltic ice sheet sector due to increased precipitation. Lagerlund (1987) even suggested the evolution of a number of marginal ice domes in order to explain the Late Weichselian Baltic ice advances over Denmark and southern Sweden. At the same time the rising sea level by way of calving prevented the Norwegian ice from reaching the Danish area, even though this part of the ice sheet may also have experienced increased precipitation. In what follows, an overall examination of the deglaciation rates and mechanisms within the Danish sector in the Late Weichselian will be performed.

Late Weichselian Deglaciation Rates

Consider the palaeoglaciological consequences of Figure 1 for a moment. Mean deglaciation rates vary from 60 to

200 ma^{-1}(m/year), lowest in the northern area, which was affected by the Younger Toldia transgression, and highest in the southeastern part of Denmark, where terrain was generally above sea level. Obviously, the dates and ice sheet margins given in Fig.1 are only approximate, but the corresponding mean deglaciation rates should nevertheless be within the correct order of magnitude. On the other hand, these deglaciation rates can be minimum values only, as the geomorphology indicates the presence of interveining readvance lines. This is why, real deglaciation rates may well have been in excess of 200 ma^{-1} in southern Denmark. As a conservative estimate, a mean frontal retreat of 100 ma^{-1} is adopted as representative for the period 18-17 ka BP in the southeastern part of the Danish area.

Modern Deglaciation Rates

Deglaciation rates measured at modern glaciers within the present century are usually of an order of magnitude smaller than the Danish Late Weichselian conservative estimate of 100 ma^{-1}. Especially from 1930 to 1960 AD was a time of what is usually seen as a period of substantial back wasting of modern glaciers, but the associated frontal retreat rates were usually within a range from 5 to 15 ma^{-1} (see, e.g. ÖAV-Mitteilungen, various dates). These modern deglaciation rates are far below the estimated Danish Late Weichselian rates. The same applies to modern rates obtained from the ice cap Myrdalsjökull in Iceland, where maximum mid-century deglaciation rates were about 10 to 25 ma^{-1} (Krüger and Humlum 1981).

At localities where a glacier terminates in a large water body deglaciation rates of about 100 ma^{-1} are normal. Recent investigations by one of us (Humlum, in prep.) at maritime outlet-glaciers along the present ice sheet margin in central West Greenland have demonstrated 20th-century rates of both advances and retreats of 50-200 ma^{-1}.

Late Weichselian Surface Ablation

The infrerred high Late Weichselian deglaciation rates in southern Denmark (terrestial environment) in this way point toward a discrepancy hard to explain for a non-maritime environment. We will, therefore, now consider the amount of vertical ice ablation corresponding to the horizontal deglaciation rates.

To estimate the amount of vertical net ice wastage associated with frontal deglaciation rates such as the above conservative 100 ma-1, it is necessary to make some estimates concerning the surface form of the Late Weichselian ice sheet in South-western Scandinavia.

Reconstructions of the Weichselian and Wisconsin ice sheets have been attempted on several occasions (see, e.g. Andrews 1982, Boulton et al. 1985). Notably most theoretically based reconstructions tend to generate symmetrical ice covers with large ice thicknesses achieved short distances behind the ice sheet margin, as do empirical reconstructions based on the two modern ice sheets in Greenland and in Antarctica (see, e.g. Paterson 1972, Sugden 1977, Humlum et al. 1978, Denton and Hughes 1981, Andrews 1982, Boulton et al. 1985, Hughes 1985). In contrast to this Peltier's (1981) reconstruction of the Laurentide Ice Sheet based on uplift data suggests generally thinner ice and especially thin ice cover over the prairies in North America. Also observations made by different workers on ice marginal features (see, e.g. Mathews 1974, Clayton et al. 1985, Beget 1987) indicate this to have been the case at certain other localities in North America. Reeh et al. (1983), Boulton et al. (1985) and Fisher et al. (1985) then introduced deformable beds into the ice flow modelling exercise. The introduction of deformable glacier beds into glacier modelling has the general effect of producing areas of thinner ice and removes much of the geometric ice sheet symmetry known from earlier reconstructions. In the present case, a modified version of the model developed by Fisher et al. (1985) was used to reconstruct the Late Weichselian North European Ice Sheet around 17.5 ka BP. The software represents a refined version of the model developed by Reeh (1982), which for the Greenland Ice Sheet was able to reproduce successfully all the present major ice divides, ice streams and centres. Also flow line trajectories were accurate and the model's surface elevations were at most in error by 10% for the Greenland case. The graphic result of the Danish Late Weichselian exercise is shown in Fig.3. The model uses a simple ideal plastic ice rheology that is rather insensitive to unknown parameters such as, e.g. mass balance parameters and takes as input only the margins of the former ice sheet, the present day topography, and an assumed yield shear stress for the glacier ice.

Only the south-western part of the Late Weichselian Ice Sheet is shown in Fig.3. Glacier surface gradients are visibly larger along the Swedish west coast than over the Danish area, which is the result of an assumed difference as to basal yield shear stress, for which a range of 0.5 to 1.5 bars was adopted as a "normal" range (1 bar = 10^5Nm^{-2}) in the case of Sweden, where the glacier bed consisted of solid bedrock. Lower values of 0.1 to 0.5 bars were adopted for Denmark and the areas south of Sweden, due to a cover of assumed deformable sediments found there.

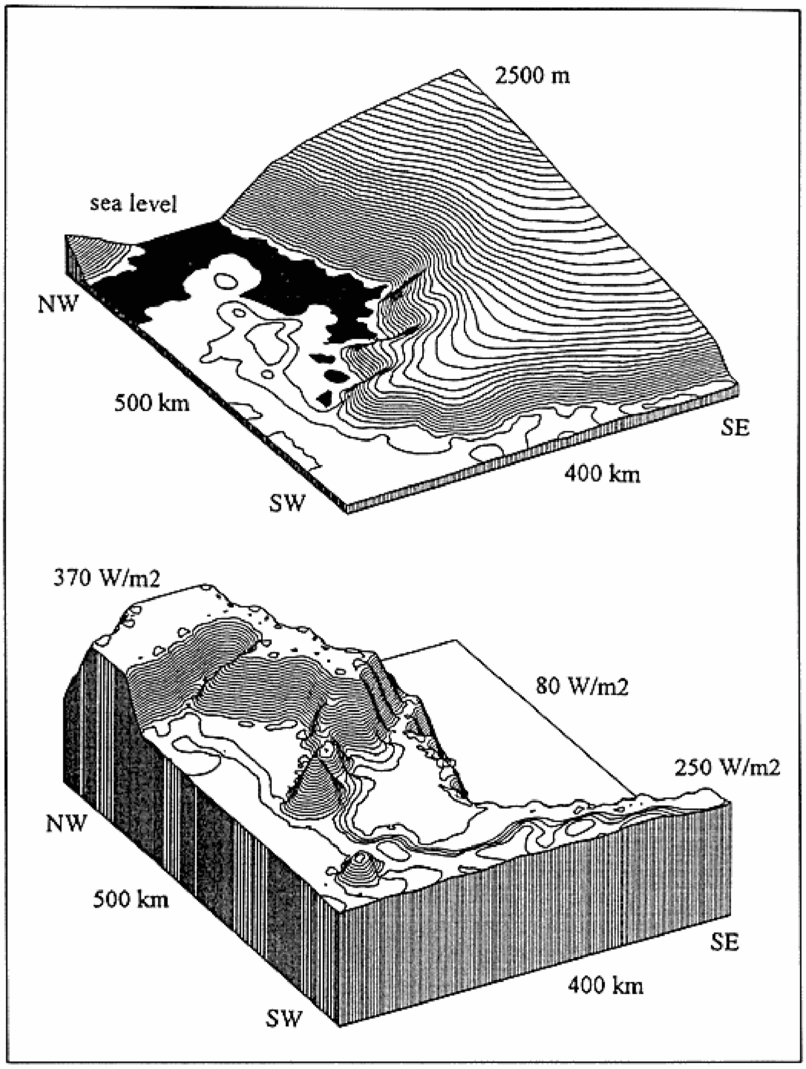

Fig.3. Upper diagram shows a 3D-reconstruction of the 17.5 ka BP Late Weichselian ice sheet in the Danish area; compare with Fig.1. Sea is shown in black. The western part of Denmark and northern part of Germany are seen as flat land areas in front of the ice sheet. Vertical exaggeration 35 times. Equidistance 50 m. Seen from the SW. The lower diagram shows the calculated distribution of mean daily short-wave radiation balance for the Late Weichselian ice sheet on July 1st., 17.5 ka BP, at clear-sky conditions. Same geographical point of view as that used in the upper diagram. Equidistance 5 Wm^{-2}. Highest net radiation values are calculated for the sea surface. The ice-free terrain is characterized by values around 250 Wm- 2. Typical values for the ablation area are 230-240 Wm^{-2}. Lowest values (about 80 Wm^{-2}) are calculated for areas above the equilibrium line.

According to the model output (Fig.3), ice surface altitudes of 500 m a.s.l. were generally reached 15-20 km behind the glacier margin in the Danish area around 17.5 ka BP, and about 200 km from the margin altitudes of 1,000 m a.s.l. were reached. In contrast to this, calculated ice surface altitudes of 1,000 m a.s.l. were found only 50 km east of the glacier margin along the Swedish west coast, due to the higher basal shear stresses assumed for this area. Correcting for isostasy, and taking the present Danish 17.5 ka BP glacier bed as an almost horizontal surface, an ice surface altitude of 1,000 m approximately corresponds to a simultaneous ice thickness of about 1,500 m over the south-eastern part of Denmark at 17.5 ka BP, at the position where the ice sheet wasted back to at about 17 ka BP. That is, at first sight, at this altitude only a mean net loss of about 3 m of ice was required each year from the glacier surface to satisfy the pure geometrical demands. However, the 17.5 ka BP glacier equilibrium line was probably not situated far from an altitude of about 1,000 m a.s.l., as is indicated by Late Weichselian ELA's in Central Europe and in Wales. This makes the above mean ablation requirements less meaningful, as mass balances close to the equilibrium line altitude must have been around zero or perhaps even positive for a considerable period of the time range considered. Therefore, to investigate real ablation requirements, attention must be turned towards the conditions at the 17.5 ka BP ice sheet margin, which certainly was part of the ablation area throughout the period considered.

Glacier surface profiles have been measured on the modern Icelandic ice cap Myrdalsjökull (Humlum et al. 1978). At the site of the measurement this ice cap rests on a glacier bed of loose (deformable?) sediments, and from this point of view probably represents a good analogy to the Late Weichselian ice sheet margin in the Danish area. These observations show that in order to generate a frontal recession rate of 100 m, 25-30 m of ice must be lost vertically from the glacier surface. The existence of a sloping glacier surface above the Late Weichselian terminus must have generated ice flow from the accumulation area towards the ablation area, and the above ice loss value therefore only represents a minimum ablation requirement during the Late Weichselian in Denmark. Furthermore, each winter a seasonal snow cover must have existed on the former ice sheet surface below the equilibrium line. This snow layer would first have to be eliminated by melting and evaporation each spring before any ablation could take place from the solid glacier surface below. As snow is a high-albedo feature, this would tend to narrow the length of the potential solid ice ablation season. Also occurrences of summer snowfalls would have this effect.

By way of both modelling and field observations and by introducing the concepts of a seasonal winter snow cover and active ice flow, it is suggested that a total ablation of at least 30 to 35 m of ice per year was required to generate a frontal deglaciation rate of about 100 ma^{-1} during the Late Weichselian in Denmark, provided the existence of a terrestial environment. The required total surface ablation would probably increase to about 50 ma^{-1}, if still higher frontal deglaciation rates such as 200 ma^{-1} were accepted, as discussed above.

Main Controls on Ice Ablation

The loss of mass from any point on a glacier surface by way of melting and evaporation depends upon the specific surface energy balance, which is composed of several components. At least four sources of energy are important for ablation at most modern glaciers in a terrestial environment: (1) short-wave (solar) radiation, (2) long-wave (terrestrial) radiation, (3) turbulent energy fluxes, and (4) refreezing of melt water.

The relative importance of these processes varies from glacier to glacier, but the short-wave radiation (1) balance is found to represent the most important factor at most modern glaciers (see, e.g. Föhn 1973 and Braithwaite 1981). In the ablation area of the modern Greenland Ice Sheet radiation, is found to supply about two-thirds of the energy used for ablation and turbulent fluxes supply most of the remaining one-third (Braithwaite and Olesen 1984, 1990). The importance of refreezing melt water (4) still needs clarification, but can be of considerable importance for the glacier mass balance, especially around the equilibrium line (Bøggild 1991). The latent heat flux is small on average but this is the result of substantial fluctuations between negative and positive daily values, i.e. evaporation and condensation, respectively, which nearly cancel out over longer periods (Braithwaite and Olesen 1990).

Calculated Late Weichselian Ablation

As an experiment, and in order to test the realism of Late Weichselian total ablation rates of 30 to 35 ma^{-1}, the midsummer short-wave net radiation balance was calculated for each of the segments of the 3D model of the Late Weichselian Ice Sheet shown in Fig.3. Necessary inputs in the model were aspect and slope of all individual terrain elements (N=1288), the overall surface albedo for each terrain segment, the time (17.5 ka BP), the date (July 1) and degree of cloud cover (0-100%). Since about 20 ka BP, the mean annual solar radiation at the top of the atmosphere for mid- and high latitudes of both hemispheres has been above the Quaternary average, reaching a maximum of about 9 ka BP. The present extra atmospheric solar radiation (1367 $Wm^{-2}s^{-1}$ or 236.8 $Jm^{-2}s^{-1}$) is about the average for the entire Quaternary, and is comparable to that of the last glacial maximum at around 22 ka BP (Ohmura 1987), although the climate is milder now. The variation of the solar radiation has an apparent period of about 22 ka due to the precession of the equinoxes. For purpose of the present calculation experiment, the extra atmospheric radiation at 17.5 ka BP was assumed to be 1374 Wm^{-2}.

Albedo values for different terrain surface types were obtained from standard tables in literature, from satellite imagery analysis (Kamper et al. 1991) and from personal (Humlum, unpublished) field work in Greenland. The albedo was taken as being 0.8 for the snow covered areas above the estimated ELA (assumed at about 1,000 m a.s.l), and 0.35 for the ablation area below the equilibrium line.

For the date chosen the calculation was run iteratively using time steps of one hour, and from this, mean daily net short-wave radiation values were calculated for each terrain segment. For each time step in the calculation the

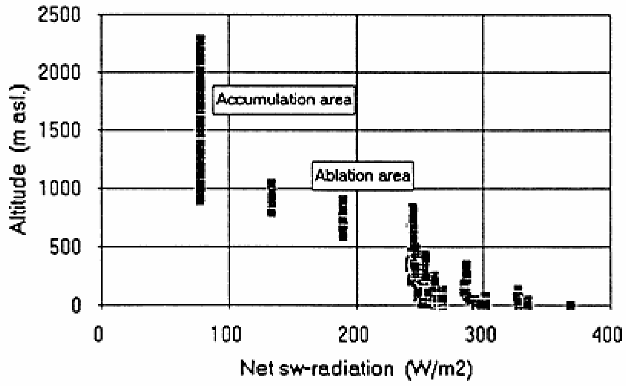

Fig.4. Altitudinal distribution of calculated mean daily short-wave radiation balance for the Late Weichselian ice sheet on July 1st., 16 ka BP, at clear-sky conditions. Equilibrium line at about 1000 m asl. Discussion in text. See also Fig.2.

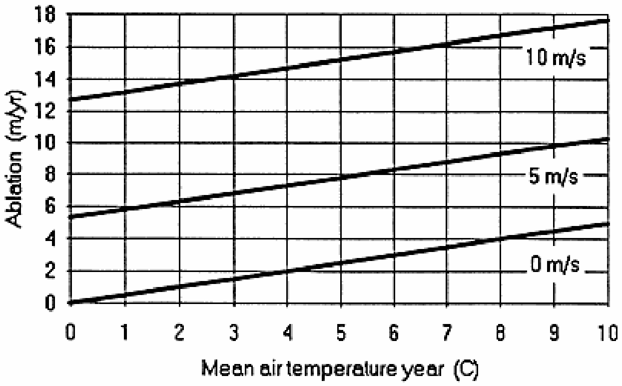

Fig.5. Diagram showing empirical relations between yearly mean air temperature, wind velocity and snow/ice ablation. Discussion in text.

software automatically checks for a topographic-induced shadow. The calculations were run for different values of cloud cover (0%, 25%, 50%, 75% and 100%). Figures 3 and 2 show graphic and numerical outputs of the calculation for clear-sky conditions (cloud cover 0%) on the mean short-wave net radiation, at 17.5 ka BP, July 1. These input values were chosen to obtain information on the maximum short-wave net radiation during the ablation season in the Late Weichselian. Figure 3 shows the overall areal distribution of net radiation values, while Fig.4 shows the corresponding altitudinal distribution.

From both Fig.3 and 4, thus representing a sunny midsummer day in Denmark during the Late Weichselian, average values for the mean daily short-wave net radiation are seen to have been within a probable range from 240 Wm^{-2} to 250 Wm^{-2} in the lowermost part of the ablation zone. Overcast conditions (cloud cover 100%) reduce the short-wave balance to about 150 Wm^{-2}. Adopting the high value of 250 Wm^{-2} to represent a maximum mean daily summer value, and extending this to the months of June, July and August, representing the Late Weichselian ablation season, we calculate a total maximum short-wave energy input of about 1950 MWm^{-2} or 338 MJm-2 for the whole ablation period. If all of this energy is used for melting ice, about 4.5 m of ice would then have been lost each summer from the glacier surface near the ice sheet margin. As stated above, this clearly represents a maximum value for ablation caused by short-wave energy input, and a more realistic value may have been about 3 m of ice, when taking periods of overcast conditions, etc., into consideration. On the other hand, also other mechanisms are active ablating ice, although usually being subordinate to the short-wave energy input (see discussion above), and the above calculation should only be taken as a rough indication of an order of magnitude.

Summing up, the calculation experiment indicates the Late Weichselian mean yearly total ice ablation in Denmark at 17.5 ka BP probably to be within a range from 4 to 6 m ice per year, including all mentioned ablation mechanisms. Almost certainly, it must have been less than 10 ma^{-1}. Introducing the effect of active ice flow towards the glacier terminus and the presence of a seasonal snow cover probably reduce the yearly net ablation to a realistic value below 5 m of ice.

A yearly net loss of about 5 m of ice (total ablation less than 10 ma^{-1}) from the glacier surface is far below the above estimate of 25-30 ma^{-1} (total ablation 30-35 ma^{-1}) made on geologic grounds, and suggests that the Late Weichselian geologic estimate should be tested against other independent criteria. This can be achieved by way of Fig.5. The three graphs in the figure represent empirical relations concerning snow/ice ablation used by the US Army Corps of Engineers, incorporating the effect of both air temperature and wind velocity. According to these relations, about 10 m of ice would today melt per year in Denmark (8°C, using a mean wind velocity of about 5 ms^{-1}). This estimate on modern potential ice ablation is thus far below the Danish Late Weichselian estimate. Also results obtained by Braithwaite and Olesen (1984) indicate the presence of an substantial and interesting discrepancy between the estimated Late Weichselian ablation rates and the energy input available then.

Dicussion

From the above analysis we have apparantly identified a major unsolved problem concerning the Late Weichselian deglaciation of Denmark and adjoining areas. On one hand the knowledge of Late Weichselian ice-marginal lines and associated datings are well founded. On the other hand data on the then available energy input suggest that estimates of Late Weichselian deglaciation rates derived from geologic knowledge are much too high.

Both the geologic knowledge and the energy calculations must be considered sound and internally robust, and we do not consider it likely that major errors will be found within either approach. Assuming this to represent a correct assessment, the reason for the apparent deglaciation paradox should probably be sought within our overall conception of the Danish Late Weichselian environment.

Several deglaciation models are presently at hand (see, e.g. discussions in Berthelsen 1979, Berglund 1979, Lagerlund et al. 1983, Lagerlund 1987, Houmark-Nielsen 1987, Lidmar-Bergström et al. 1991), but most models appear to operate with the implied condition that deglaciation generally took place within a terrestrial environment, with no further specification of environmental characteristics. However, three environmental factors may deserve consideration in order to gain insight into the reasons for the above apparent deglaciation paradox.

(1) Surface form of the ice sheet. The influence of different shear stress ranges at the glacier base was shortly outlined earlier in this paper. Assuming lower than normal shear stresses due to a deformable substratum will produce a flatter ice sheet surface profile, requiring less net ablation in order to satisfy the requirement of frontal deglaciation rates of about 100 ma^{-1}. This point was taken into consideration during calculation of the 3D-model (Fig.3), assuming yield stresses from 0.1 to 0.5 bar for the ice sheet covering Denmark and areas south of Sweden. We do not find a further reduction to values below 0.1 bar realistic. Several field observations from Denmark show that considerable friction must have existed between the Weichselian ice sheet and the substratum. Signs of this are, e.g. push moraines, thrust features, glacial flutes, drumlins and glacial striae on the surface of large rock fragments and solid bedrock (see, e.g. Krüger 1970, Berthelsen 1978, Humlum 1979, Houmark-Nielsen 1987). Experimentally reducing the slope of the marginal ice sheet surface profile to about half of that shown in Fig.3, still results in a total ablation requirement of impressive 15-20 ma^{-1} at the glacier margin.

(2) Marginal water bodies. Isostatic depression of the crust below the ice sheet must have been considerable. Both on theoretical and empirical grounds, it has been suggested that the isostatic depressed region would extend 50 to 100 km beyond the margin of a huge ice sheet such as the Weichselian in North Europe, due to flexure of the crust (see, e.g. Brotchie and Silvester 1969, Birchfield and Grumbine 1985, Hyde and Peltier 1985). Near the glacier margin the depression probably amounted from about 50 to 100 m, thus producing a regional topographic low along the ice sheet margin. If so, melt water must have accumulated in several places within this depression, producing numerous large and small water bodies (Fig.6 and 7), tending to migrate with the ice sheet margin as this undergoes advances and retreats. At certain times, the ocean itself may even have transgressed into this isostatic induced topographic low. As the outflow of material in the asthenosphere takes time, the isostatic adjustment must lag the change in load upon the crust. During periods of back wasting, when the ice sheet margin retreated across still depressed regions, the tendency towards generating marginal lakes must have been especially pronounced. The numerous Late Weichselian kame-hills and former

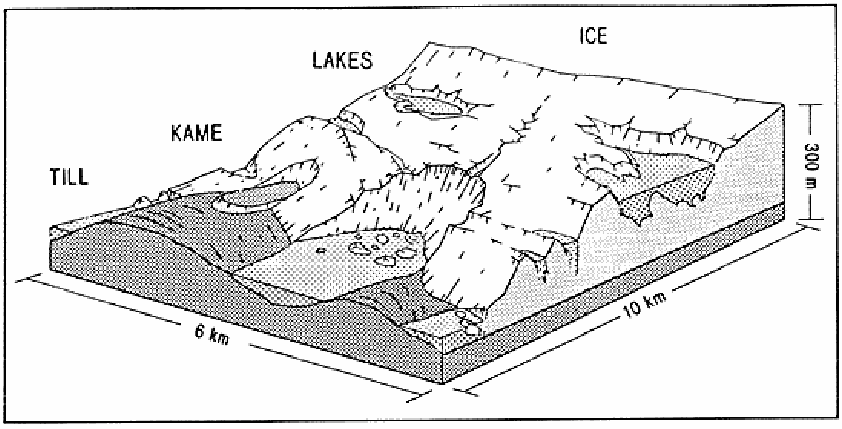

Fig.6. Idealised diagram showing environmental features suggested as being important for the Late Weichselian deglaciation of Denmark. The occurrence of high catabatic winds may also have contributed to high ablation values.

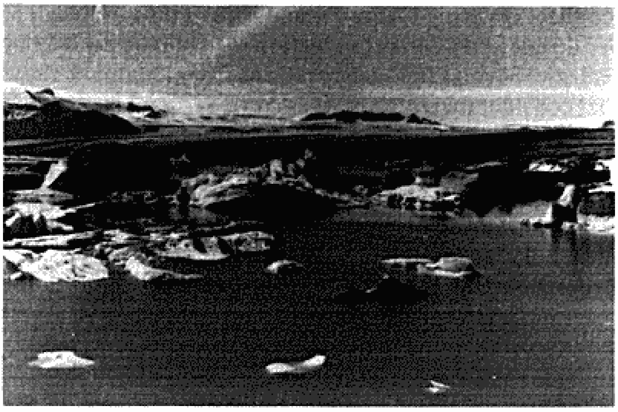

Fig.7. The present margin of Breidamerkurjökull, Iceland, with marginal lake.

ice-dammed lakes found within the Danish area (Fig.8 and 9) also clearly point towards the frequent occurrence of temporary water bodies at the ice sheet margin.

Recent investigations (Humlum, in prep.) along the present ice sheet margin in central West Greenland has shown 20th-century rates of both advances and retreats to be of about 50-200 ma^{-1} where the ice sheet margin ends in a marine or lacustrine environment, without being floating, while corresponding rates are 0-10 ma^{-1} at places where the margin stands in a terrestrial environment. Where floating of the glacier terminus occurs, rates are usually 100-400 ma^{-1}. Calving and accelerated melting of ice caused by contact with liquid water is considered the two main reasons for the observed high retreat rates in the marine/lacustrine environment. Furthermore, calving will tend to produce a cliffed margin, a feature which in itself will tend to increase ice ablation during periods of low sun angles (Chinn 1987), thus extending the effective length of the ablation season.

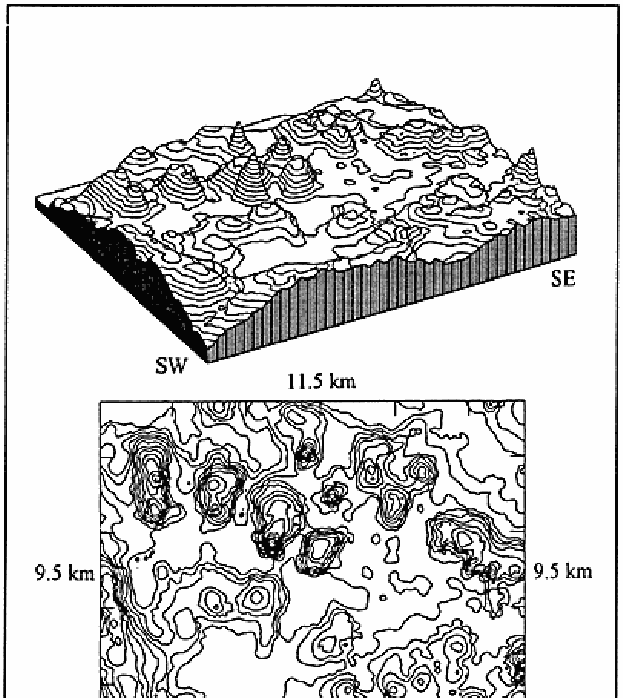

Fig.8. Weichselian landscape dominated by numerous kame-hills SE of Jyderup, NW-Zealand. Water flowed into the former lakes from NE. Equividistance 4 m.

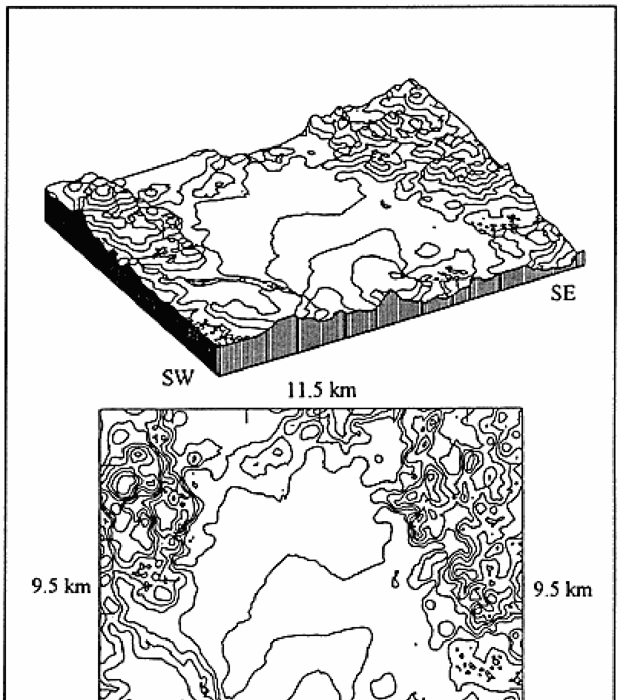

Fig.9. Bottom surface of former Late Weichselian ice-dammed lake, near Skullerupholm, W of Roskilde, central Zealand. Water flowed into the lake from the S. NW and NE of the former lake several kame-hills are seen. Equividistance 4 m.

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Holocene Relative Sea-Level Changes Indicated by Morphostratigraphic Sequences; Sinigfik, Disko Island, West Greenland.

Morten Rasch & Niels Nielsen

Morten Rasch & Niels Nielsen: Holocene Relative Sea-level Changes Indicated by Morphostratigraphic Sequences; Sinigfik, Disko Island, West Greenland. Geografisk Tidsskrift, Danish Journal of Geography 94:xx-xx, Copenhagen, Dec. 1994.

A morphostratigraphic method is introduced in a study of Holocene relative sea-level changes at Sinigfik on the south coast of Disko Island, West Greenland. The method allows detection of relative sea-level rise interrupting the general Holocene emergence. It is concluded that the Holocene relative sea-level history at Sinigfik was one of steady emergence prior to c. 3 ka B.P. A complex morphostratigraphic sequence near the present coastline might result from two emergence/submergence events within the last millenium. The geomorphology of the present coastline indicates extensive coastal recession, probably resulting from a relative sea- level rise at present.

Keywords: *Beach ridge plain, emergence curve, Holocene, morpho-stratigraphy, relative sea-level changes, Disko Island, West Greenland.*

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During the last thirty years a number of emergence curves representing Holocene relative sea-level changes from local areas in Greenland have been published (North Greenland: Fredskild 1969, Weidick 1972, Bennike 1987, Funder og Abrahamsen 1988. East Greenland: Washburn & Stuvier 1962, Lasca 1969, Weidick 1972, Street 1977, Funder 1978. West Greenland: Weidick 1972, 1976 Kelly 1973, 1979, 1985, Donner & Jungner 1975, Ten Brink 1974, 1975, Funder 1979, Fredskild & Møller 1981, Frich & Ingolfsson 1990, Ingolfsson et al. 1990). Several problems are related to the construction of emergence curves (Weidick 1972, Kelly 1973, Ten Brink 1974, Donner og Jungner 1975), and as a result probably all published curves from Greenland only show a rough trend of Holocene relative sea-level changes (Funder 1989).

The goal of this paper is to describe Holocene relative sea-level changes at an arctic coast in mid West Greenland; especially focusing on the development during the last 3 ka. To avoid the uncertainties of traditional emergence curve construction, a new morphostratigraphy

(3) Increased ablation due to strong winds. During glaciological field work in both West and East Greenland, one of the authors have several times observed that the action of strong, dry winds within few hours can result in heavy ablation from a glacier surface. Wind action as this especially appears to be of importance in areas such as the Ammassalik area in south-eastern Greenland, where dry catabatic winds are frequent. One visible result of the wind controlled ablation is the rapid production of a very smooth glacier surface in the ablation area. Under normal summer conditions this part of a glacier is usually characterised by high surface roughness. The importance of wind velocity for ice ablation can also be seen from the empirical relations established by the US Army Corps of Engineers (Fig.5). Certain sectors of the ablation area of the Late Weichselian ice sheet may have experienced heavy catabatic winds, depending upon the ice sheet topography and the track of wandering meteorological depressions. In sectors such as these, ablation may well have been considerably above average, partly due to increased evaporation, and partly due to much of the winter's snow being swept away from the glacier surface, exposing the solid low-albedo glacier surface below to short-wave radiation. An increased storm activity along the southern ice sheet margin (Oerlemans and Venekar 1981, Manabe and Broccoli 1985, Oerlemans 1991) during the Late Weichselian may have been the meteorological background for an increased outflow of strong catabatic winds, as is presently the case in SE Greenland.

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