Glacier behaviour and the influence of upper-air conditions during the Little Ice Age in Disko, central West Greenland.

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An inventory of 205 glaciers and small firn areas in southwestern Disko, central West Greenland, display large differences as to the amount of ice recession since the end of the Little Ice Age. Especially high-situated ice bodies facing N and NW have experienced a substantial retreat, while other ice bodies have not. The cause for this difference is investigated by considering the amount of vertical equilibrium line displacement since the end of the Littel Ice Age. From this, it is argued that especially variations in upper-air wind conditions -as measured at the 850 mb level- are responsible for the observed heterogeneous glacial behaviour.

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The existence and importance of past widespread glaciation were first recognized by Agassiz (1840) and the direct connection between glacier behaviour and climate was refined by Matthes (1942) and Ahlmann (1948, 1953). Later work by Nye (1960, 1963), Meier (1965), and Hoinkes (1968) demonstrates that a definite relationship exists between climate, energy exchange, mass balance, and the dynamic response of a glacier, and that the connecting links between these factors may explain the current behaviour of glaciers in response to the climate of the present and recent past. From this, reconstructions of past climates has been attempted from various indications on former glacier extensions and snow-lines. Typically, the distribution of moraines and mean cique floor elevations have been the object for investigation (see e.g. Flint 1971, Miller 1961, Porter 1964, Ito and Vorndran 1983).

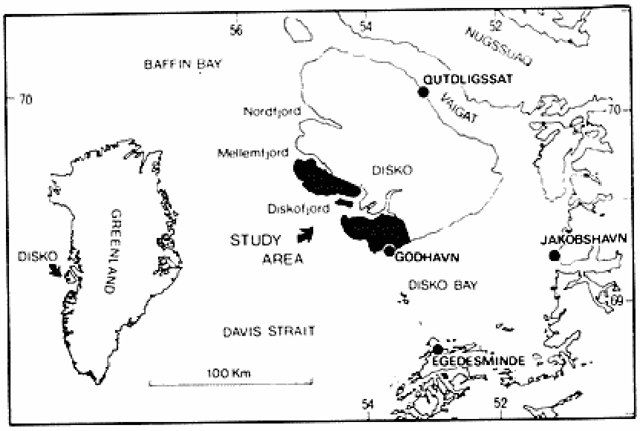

Fig. 1. Location map showing the study area and location names.
Fig. 1. Oversigtskort visende undersogelsesområdet og stednavne.

Palaeoclimatic inferences drawn from geomorphologic data should be based on an understanding of the relationship between climate and glacier fluctuations. Complex interactions exist between prevailing regional and local climatic conditions, regional and local topography, energy exchange at the glacier surface, mass-balance pertubations, and glacial dynamics (Meier 1965, Andrews et. al. 1970). Glacier fluctuations represent integrated responses to these factors, and due to differences as to the above factors, even glaciers within a geographically restricted area may well display different responses on identical overall climatic changes. This obvious represents a potential pitfall for palaeoclimatic studies using geomorphologic data on moraines, cirque floors and former snow lines, especially when the data are obtained from areas at present without glaciers, so that local variations as to glacial dynamics may not be studied.

The purpose of the present paper is to present an inventory on a group of glaciers in Disko, central West Greenland, to all appearances representing a rather homogeneous group, but who nevertheless since the close of the Little Ice Age has displayed a very uneven response to climatic changes. The reason for this heterogeneous behaviour will be discussed. In all likelihood a controlling factor is differences as to altitude above sea level and thereby different influence of upper-air meteorological conditions.

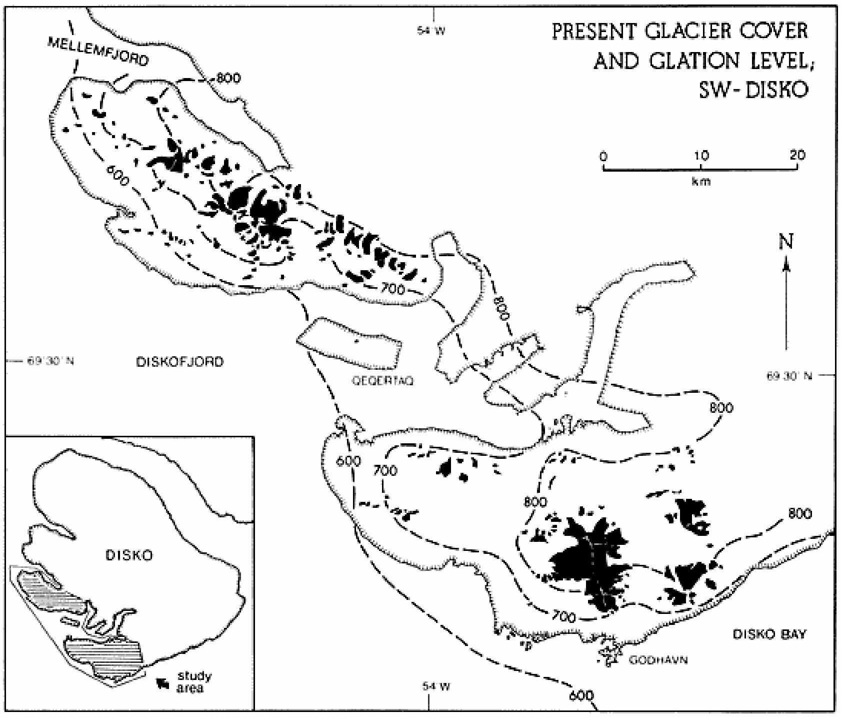

Fig. 2. Map showing the study area with its present ice cover, and the present glaciation level. Altitudes in metres above sea level.

Fig. 2. Oversigtskort visende undersøgelsesområdet, dets nuværende isdække samt glaciationsniveauet. Højdeangivelser i meter over havniveau.

STUDY AREA

The study area is the southwestern part of the island Disko, central West Greenland (about 70°N, Fig. 1). The area consist of two peninsulas, 465 km² and 640 km², situated northwest and south of Diskofjord, respectively, and the 30 km² island Qeqertaq in Diskofjord (Fig. 2). This part of Disko consist of Tertiary plateau basalts, and the landscape is dominated by cirque carved lava plateaus and U-shaped walleys. Extensive top plateaus characterize the mountains in the southern peninsula (Fig. 3), while plateaus are less extensive in the northern peninsula. In the central and northern part of this peninsula the landscape approaches an alpine landscape (Fig. 4). The upper land surface rises from about 500-600 m asl. in the western part of the two peninsulas to above 1050 m asl. in the eastern part of the peninsulas. The island Qeqertaq reaches an altitude of about 600 m asl.

Climatic conditions within the study area can only be inferred in overall outlines, as only one meteorological station is presently being operated on Disko, in the town Godhavn/Qeqertarsuaq at the southern coast (Fig. 1). In Godhavn the mean annual air temperature was -3,5° during the period 1950-69, coolest month was March (-14.8° C), and warmest month July (7.4°C). Mean annual precipitation was 406 mm (water equivalent), of which about 75% usually falls during the period June-December, while the remainig part of the year is comparatively dry. Most precipitation falls in connection with advection of moist, maritime air masses along the Davis Strait from south and southwest. In Godhavn, at sea level, snow is the dominant type of precipitaion from late September to late May. The prevailing wind is from east and northeast, with the exception of the period May-August, where southwesterly and westerly winds dominate. Mean wind speed at sea level has a maximum during autumn and early winter, while it has a minimum in the period February-April. In general, the weather pattern in coastal central West Greenland is dominated by advection of moist air masses from S along the Davis Strait during the summer and autumn, while dry and cold air flowing off the Greenland Ice Sheet dominates the weather pattern during the remaining part of the year.

In Godhavn the sun is below horizon from late November to middle January, and the period with midnight sun is from last half of May to late in July. At summer solstice, solar radiation available daily (in the absence of atmosphere) exceeds the maximum radiation ever available at the equator.

According to inhabitants in Godhavn and local fishermen, also the southwestern part of Disko is characterized by a polar, maritime climate; in general much of the same nature as that experienced at Godhavn. This applies espcially for the exposed outer coast, where the orographic precipitation is at maximum. Moving eastwards along Diskofjord, climate rapidly becomes more continental. This overall picture is supported by the authors personal experience gained during several journeys within the study area in connection with a three-year stay in Godhavn (1983-86).

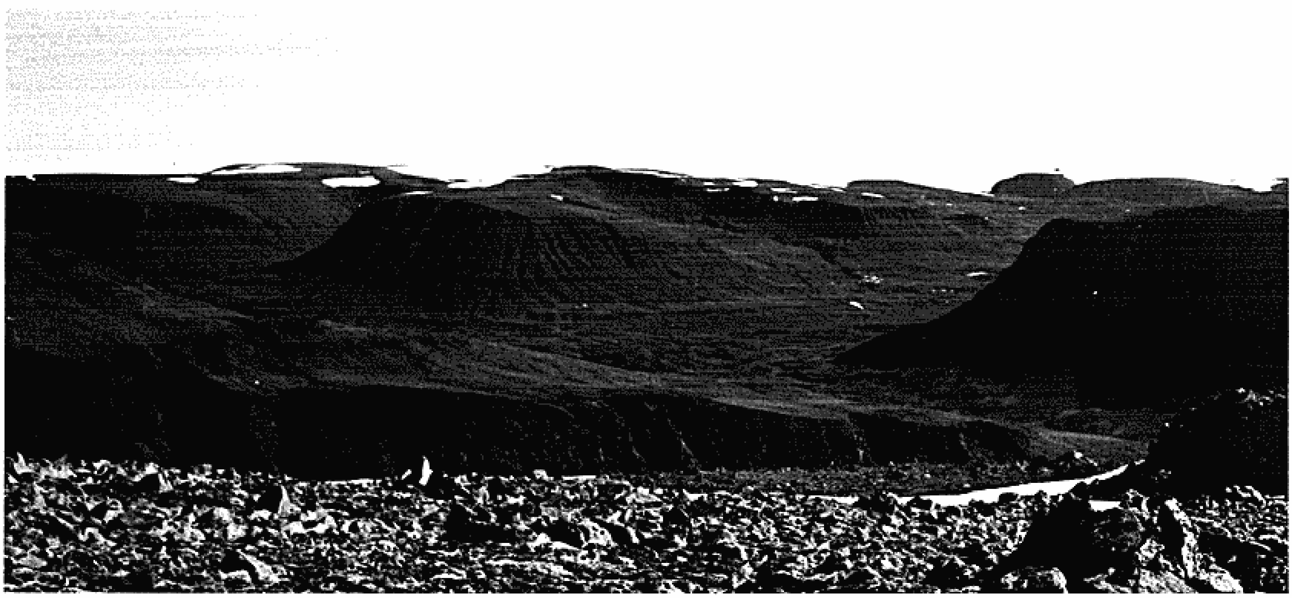

Fig. 3. Plateau mountains in southern Disko, 15 km north of Godhavn. The general top level is about 900 m asl., and the valley bottom visible right of the center is about 400 m asl. Seen towards northeast. 08.06.1985.

Fig. 3. Plateaubjerge i det sydlige Disko, ca. 15 km nord for Godhavn. Det generelle topniveau er omkring 900 m over havniveau, mens dalbunden til højre for billedmidten ligger i ca. 400 mt's højde. Set mod nordøst. 06.08.1985.

At present Disko (about 8575 km²) supports an extensive local glaciation. A total of almost 1000 ice caps, valley glaciers, cirque glaciers and isolated firn areas have been mapped by the author from aerial photographs recorded in the years 1953 and 1964. Together, almost 20% (1610 km²) of the island is presently covered by glaciers. Maps showing the present glaciation level (GL) in Disko have been prepared by the author (Humlum 1985 and 1986).

Within the study area 205 individual glaciers and isolated firn areas presently exist. Figure 2 display the distribution of these ice bodies as well as the present glaciation

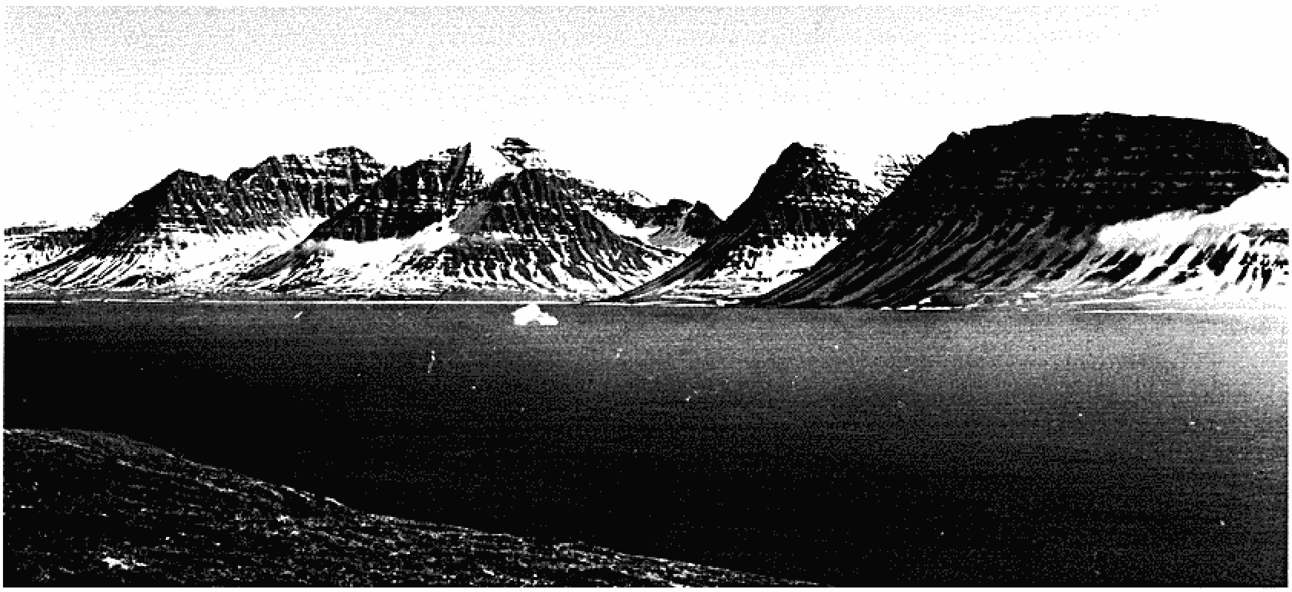

Fig. 4. Alpine landscape at the southern coast of Mellemfjord. Highest mountain tops are at about 1000 m asl. Seen towards southeast 07.07.1978.

Fig. 4. Alpint landskab ved Mellemfjords sydkyst. De højeste toppe når ca. 1000 m over havniveau. Set mod sydøst. 07.07.1978.

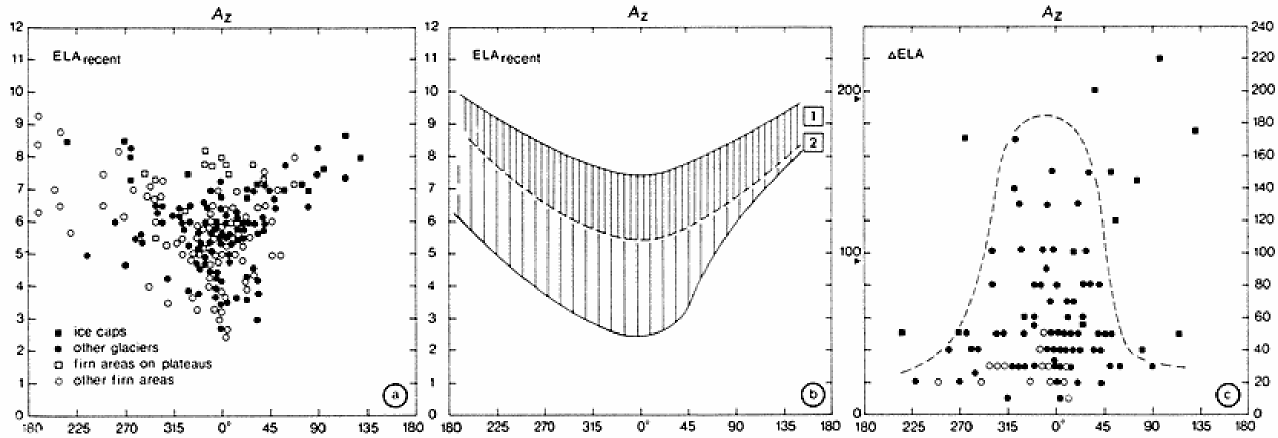

Fig. 5. Diagrams shoving (a+b) present equilibrium line altitudes (ELA), and (c) vertical equilibrium line displacements (ΔELA) since the end of the Little Ice Age. Orientation »Az« of equilibrium lines in 360°-scale; 0°=north. Discussion in text.

Fig. 5. Diagrammer visende (a+b) højden af nuværende ligevægtlinier (ELA) i undersøgelsesområdet, samt (c) den vertikale forskydning af ligevægtlinier (ΔELA) siden »Den lille Istids« ophør omkr. år 1900. Ligevægtsliniens orientering er angivet ved en 360°-skala; 0°=nord. Videre diskussion i teksten.

level in the area. Glaciers and firn areas were mapped in the field or from the above aerial photographs from 1964.

The largest coherent ice cover within the study area is the 85 km² ice cap Lyngemarkens Iskappe N of Godhavn (Fig. 2). Ten outlet glaciers radiate from this ice body. Almost all other glaciers within the study area are small cirque- or valley glaciers, usually not exeeding a few km² in size. Most glaciers face N or NW, but with the exception of the sector around SSE glaciers are found with almost any aspect (Fig. 5).

Since about 1895-90 AD, glaciers in Disko have been receeding, only interrupted by a small readvance about 1930-35 (according to the authors own lichenometric observations). Today, the terminus of most glaciers within the study area are still melting back, although several glaciers appear to be thickening in their upper reaches.

Talus production is intensive in Disko, and many glaciers therefore carry a substantial supra- and englacial load. Moraines dating from the Little Ice Age (ended about 1900 AD, Weidick 1968) are therefore dominated by talus-like material and are often very conspicious (Fig. 6). Due to the intensive talus production, also rock glaciers are frequent within the area (Humlum 1983).

During an inventory of the Littel Ice Age (LIA) extension of glaciers in Disko, a difference as to the LIA extension of glaciers facing N-NW and otherwise became apparant. Several glaciers facing N or NW (as indicated by the orientation of the equilibrium line) has experienced a considerable retreat since the end of the LIA, while few glaciers facing otherwise then reached significantly beyond their present terminus. Below, the meteorological background for this dissimilarity as to glacial response will be investigated.

RECENT EQUILIBRIUM LINE ALTITUDES

As variations in the equilibrium line altitude is a sensitive measure of mass balance changes for a glacier, the above problem is investigated by considering equilibrium line altitudes within the study area.

No systematic mass balance measurements have been undertaken on glaciers in Disko, and the equilibrium line altitude (ELA) for individual glaciers thus had to be determined by way of an indirect approach. Several techniques are available, and for a comprehensive review the reader is referred to the paper by Gross et al. (1977). In most cases the following visual technique was adopted for estimation of the local ELA: Where possible, the ELA for a glacier considered was determined as the level, below which medial moraines or other englacial debris are cropping out on the glacier surface (Lichtenecker 1938, Visser 1938). As most glaciers within the study area are situated in cirques encompassed by prominent headwalls, usually yielding large amounts of fresh talus, the ELA could be estimated by this procedure at the majority of glaciers. Observations were carried out in the field in a few cases, but most cases were decided by use of aerial photographs recorded shortly before the close of the ablation season 1964 (August 27th). Usually, the first lasting winter snow appears on the glaciers in Disko early September.

The official weather reports from the Danish Meteorological Institute show precipitation at Godhavn in July-August 1964 to be somewhat above normal; 124.9 mm water equivalent against a mean of 98.1 mm for the period 1950-69. The mean air temperature July-August 1964 was 5.5°C, against a mean of 7.3°C for the period 1950-69. Provided the record from Godhavn is fairly representative for the study area as a whole, any discrepancy between the current ELA_{mean} and the ELA_{1964} as determined by the above procedure is likely to be that the ELA_{1964} would be somewhat below the current ELA_{mean} Furthermore, because debris comprising medial moraines and other supraglacial load originally may have been incorporated in the upper part of the accumulation area, close to the headwall, it will usually crop out on the glacier surface some distance below the equilibrium line. The above visual inspection thus only provides a minimum altitude for the equilibrium line. As most glaciers within the study area however are rather short, less than 2 km, this potential error is considered unlikely to disturb the overall pattern very much.

Summing up, the visual estimation of the ELA_{1964} may result in a value somewhat lower than the current ELA_{mean}. This should be carried in mind in what follows. As a first approximation, the results of this visual procedure will however be applied in the present context.

For glaciers facing E or W, the equilibrium line os often at higher altitude near the northern flank of the glacier than at the southern flank. This is especially the case where the glacier considered is situated shortly north of a prominent mountain ridge. In cases like these the arithmetic mean of the two extreme values was adopted as representing the ELA for the glacier. In cases of doubt, the distribution of snow-filled versus empty chutes in the headwall above a glacier was studied in some detail. In my experience from Disko, in general, chutes terminating above the local equilibrium line and facing north, west or east, usually are filled with snow at their lower end at the close of the ablation season, while chutes ending below are not. Finally, if still in doubt, the overall surface form of the glacier was considered. The ELA was then approximated as the level where the surface changed from concave to convex (see also Andrews and Miller 1972).

For five glaciers, neither of the above tecniques appeared adequate. The ELA was then estimated using an assumed steady-state accumulation areas ration (AAR) of 0.65. Several studies indicate that for steady-state glaciers the accumulation area/total area varies between 0.6 and 0.7 (see e.g. Meier and Post 1962, Glen 1963, Grosswald and Kotlyakov 1969, Gross et al. 1977).

In order to obtain supplementary observations on the current ELA, the aerial photographs were also used to in-

Fig. 6. Unnamed glacier with Little Ice Age moraines (arrows) in southwestern central Disko. Mountain tops at 1100 m asl., walley bottom at 350 m. Seen towards west. 08.24.1985.

Fig. 6. Unavngiven gletscher i det sydvestlige central-Disko. Foran gletscheren ses (pile) morænesystemet fra Den lille Istid. Bjergtoppene er omkr. 1100 m høje, mens dalbunden ligger i ca. 350 mt's højde. Set mod vest. 24.08.1985.

vestigate the distribution of large snow banks (isolated firn areas), known to or supposed to represent permanent features. As no significant movement is expected to occur within these snow accumulatins, the lower altitude of these features at the end of the ablation season was adopted as an approximation of the local ELA. Only snow banks/firn areas situated in terrain not due to its topography excluding a lower extension than the actual observed – e.g. by way of a steep cliff – were considered. In case of doubt, the presence of a frontal moraine ridge or a bergschrund (indicative of significant deformation) was used to discriminate between true glaciers and permanent snow banks/firn areas.

By the above techniques, the current (1964) local ELA was estimated for 106 glaciers and 93 isolated firn areas within the study area. For 6 firn areas the character of the adjoining terrain made an estimation impossible. The resulting 199 ELA_{1964} estimates are plotted in figure 5a. Height determinations were mainly derived from unpublished, preliminary 1:100000 map sheets with 50 m contour intervals (Danish Geodetic Institute). Elevations between contours were interpolated and based on the topographic form between contours. In general, ELAs are estimated to be accurate within +/- 25 m. The aspect of the equilibrium line was defined as being parallel to the general glacier surface slope direction at the equilibrium line.

The pattern emerging in figure 5a appears to justify the incorporation of ELA estimates derived from large snow banks/firn areas, as both $ELA_{glacier}$ and ELA_{firn} values fall within the same overall zone of the diagram. Lowest ELA estimate is about 250 m asl. (05°), highest about 930 m (190°). A clear tendency appears to be present: The zone of ELA estimates rises gradually from N and NW towards S and SE. Notwithstanding aspect, maximum ELA estimates are however mostly derived from firn areas and ice caps situated on mountain plateaus (shown as open and filled squares in figure 5a, respectively). At these sites terrain surface gradients are small and the ice bodies are virtually unprotected against wind action. If these high-lying ELA estimates on firn areas are ignored due to the special topographic setting, the above azimuth/ELA relation becomes even more pronunced. This is emphasized by figure 5b, where the two solid lines are envelopes for all observations except for the above exposed firn areas. Within the two solid envelopes, zone »1« contains all ELA estimates derived from ice caps (filled squares). Also ice caps are usually exposed features, and ELA estimates from these features are thus all within the upper part of the overall ELA zone. Below zone »1«, zone »2« represents the observational spread of ELAs derived from glaciers and firn areas in shielded sites – e.g. cirque valleys – only. However, also some ELA values derived from ice bodies in shielded settings are found in the upper zone »1« of the overall ELA zone.

The vertical spread of the ELA zone depicted in figure 5b is assumed to represent the influenze of topoclimate within the study area, whereas the gradational rise of ELA values toward a more southerly or southeasterly aspect is assumed to be caused mainly by the overall difference as regards net radiation as a function of aspect.

LITTLE ICE AGE EQUILIBRIUM LINE ALTITUDES

In order to investigate the background for the above mentioned different glacial behaviour since the end of the Little Ice Age, the distribution of Little Ice Age equilibrium line altitudes (ELA_{LIA}) has been investigated.

The mapping of Little Ice Age ELAs was accomplished by considering the uppermost occurence of Little Ice Age moraines at the individual glaciers. These moraines are usually very conspicious in Disko (see figure 6), and, as a main rule, due to the ice movement direction, they are assumed to be deposited below the contemporary ELA only. The moraines are dated to the Little Ice Age period on account of 1) unpublished photos obtained by professor K.J.V. Steenstrup in 1898 and dr. L. Koch in 1913 (kindly placed at my disposal by dr. A. Weidick, GGU), 2) lichenometry, and 3) weathering of surface boulders on moraine crests. Naturally, not all sites have been visited in the field, but LIA-moraines in Disko are notoriously easy to identify in aerial photos due to their large size and the absence of any significant vegetation.

At 84 glaciers within the study area an estimate of the ELA_{LIA} could be obtained by this procedure, while faulty occurence and/or preservation of moraines made this impossible at the remaining 22 glaciers. Distinct marginal forms are mostly absent adjoining to the small firn areas, and the ELA_{LIA} thus could only be estimated at 14 of these features. In these 14 cases the present small ice bodies have probably seen transitional to real glaciers during the Little Ice Age, as a moraine-like ridge today is seen beyond their lower part.

EQUILIBRIUM LINE DISPLACEMENT

The ELA_{LIA} estimates were compared with the estimates on current ELAs, and the vertaical displacement of the equilibrium line at the individual sites since the Little ice Age was calculated from this. The results are depicted in figure 5c. No estimates were obtained from small firn areas situated on mountain plateaus.

At first sight the resulting plot appears to be without any clear overall pattern; most displacement values (ΔELA) are within a range of 20 to 40 m, but also values above 200 m are encountered. Moreover, even the maximum ΔELA values appear to be dispersed as to azimuth without any clear tendency.

Differentiating the ΔELA estimates according to the type of ice body leads to a much more clear pattern. As ice caps all are in a extremely exposed setting on top of the

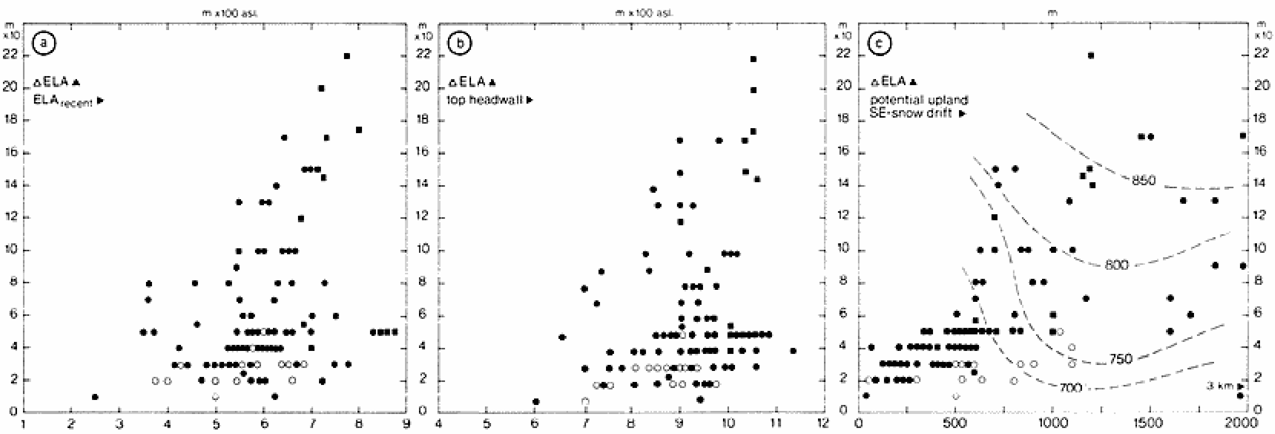

Fig. 7. Diagrams showing vertical equilibrium line displacement (ΔELA) since the end of the Little Ice Age, as function of a) the current equilibrium line altitude, b) the altitude of headwall tops above the ice bodies considered, and c) the size of the potential SE snow drift upland above/adjoining to the ice body considered. Isolines for present minimum ELA; that is, no ice bodies plotted above e.g. the 800 m isoline has a current ELA less than 800 m asl., etc. Further discussion in text.

Fig. 7. Diagrammer visende den vertikale forskydning af ligevægtslinien (ΔELA) som funktion af: a) højden af den nuværende ligevægtslinie, b) højden af bagvæggens top over de enkelte gletschere/firn områder, og c) størrelsen af det potentielle opland for snefygning fra sydøst. Isolinier for mindsteværdi for nuværende ELA; dvs. ingen gletscher plotted over f.eks. 800 m isolinien har en nuværende ELA lavere end 800 m over havniveau, osv. Videre diskussion i tekst.

mountain plateaus, ΔELA estimates (14) derived from these ice bodies are initially excluded from the analysis. The distribution of estimates derived from the remaining 84 glaciers and firn areas can then be deliminated by the envelope as shown in figure 5c. Estimates on ΔELA values less than 40 m may be encountered at any azimuth except for the sector from SE to S (no observations, see figure 5a). ΔELA values above 40 m are however only met with between WNW and NE, and the distribution appears to be symmetrical about NNW. This direction is identical to that designated as being of special interest from experience gained by an inventory on the glacier recession since the Little Ice Age (see above).

FACTORS CONTROLLING EQUILIBRIUM LINE DISPLACEMENT

The marked difference as to vertical displacement of equilibrium lines since the Little Ice Age is probably a feature derived from glacial responses on different changes in local climate at the individual ice bodies. Local climate is to a certain degree controlled by local topographic factors, and an investigation on factors controlling this heterogeneous response will therefore be attempted by considering the isolated influence of various topographic parameters on ΔELA values.

Consider figure 7a for a moment. This diagram shows a plot of ΔELA values (vertical) against the present ELA (horizontal) at the individual ice bodies. For ice bodies with the equilibrium line at comparable low altitude, the spred of ΔELA values is rather small, while it is considerable for higher ELA values. Of special interest is the fact that although the maximum values of ΔELA tend to grow as ELA increases, small values of ΔELA are nevertheless encountered for all values of ELA. As to ice body types, small firn areas (open circles) are characterized by comparatively small ΔELA values, while ice caps (black squares) dominate among high ELAs with large ΔELA spread. Glaciers in shielded topographic sites display both small and large ΔELA values.

From this one may conclude that the greater the current ELA_{mean}, the greater are the changes to encounter a very great ELA displacement since the Little Ice Age. And if one excludes the very exposed ice caps from the analysis, and also includes information from figure 5c, the preliminary conclusion is that provided an ice body considered has a northerly or northwesterly aspect (at the equilibrium line), and furthermore has a high current mean ELA, this ice body may well have experienced an above normal vertical displacement of the equilibrium line since the Little Ice Age. Only smaller vertical ELA displacements are to be expected for the remaining ice bodies within the study area.

Figure 7b elaborates further on this hypothesis. This diagram shows ΔELAs against the general altitude of the terrain surface at the top of the headwall above the glacier/ice body considered. For ice caps the altitude of the ice-free terrain adjoining to the ice body is considered. Especially in the southern part of the study area, this terrain surface may take the form of a rather smooth plane, and is not seldom of considerable horizontal extent. In the northern part of the study area, terrain is in general more alpine, and smooth top plateaus are of lesser extent.

Fig. 8. View towards southwest over the heavy glacierized central Disko. Large-scale SE snow drift surface forms are prominent. Nunataks rise 250-300 m above the glacier surface, which is at about 1100-1200 m asl. 09.07.1985.

Fig. 8. Udsigt mod sydvest over det stærkt isdækkede centrale Disko. Meget store snedrive-former præget af vind fra sydøst ses overalt. Nunatakkerne er 250-300 højere end gletscheroverfladen, der i dette område ligger i ca. 1100-1200 mt's højde. 07.09.1985.

Also from this point of view, altitude appears to represent a controlling factor on the glacial behaviour since the Little Ice Age. For ice bodies where the terrain surface above the glacier or adjoining to the glacier (ice caps only) is at relative low altitude, the corresponding $\triangle$ELA is small, while $\triangle ELA_{maximum}$ values tend to increase as greater absolute altitudes of the general terrain surface are encountered. Low $\triangle$ELAs are however still met with for some sites characterized by great terrain surface altitudes also.

HIGH-ALTITUDE METEOROLOGICAL CONDITIONS IN DISKO

The observation that ice bodies at high sites tend to display greater mean vertical equilibrium line displacement since the Little Ice Age than ice bodies at lower sites may at first sight appears to be somewhat surprising. In general, ice bodies at low sites (close to the regional GL) would more likely be expected to experience close to critical climatic conditions than would ice bodies at higher sites (high above the regional GL) within the same area. Adding to the complexity is furthermore the fact that only ice bodies facing N and NW (and at high sites) display large $\triangle$ELAs, while all other ice bodies does not. Whatever the precise cause, it must apparantly act very selectively.

Interpretations of observed ELAs and $\triangle$ELAs are affected by the nature of the ELA, being a time-transgressive feature. Climatic and topographic controls are integrated over a period of considerabel lenght, the relevant period probably being decades or even centuries for high-arctic glaciers. Earlier investigations do not agree on the nature of pertinent controls on glacierization and glacial behaviour, and, actually, the importance may well vary from region to region.

In the case of Disko, some observations on snow drift appear relevant in the present context. Large-scale eolian accumulation and deflation forms exist within the accumulation areas of many glaciers in Disko (Fig. 8). These features display a local relief of 10-70 m, and are probably not short-lived forms. Rather they are the result of a stable dominant air flow acting during several years. These air-flow forms has been mapped from aerial photographs (1953 and 1964), and the reconstructed air flow pattern responsible for the observed niveo-eolian forms is depicted in figure 9. Short arrows in eastern Disko indicate the dominant wind direction according to coastal sand dunes. The general pattern is clearly that of a dominant air flow towards N and NW, although local deviations up to 90° may occur where air masses are channeled into prominent valleys or through topographic saddles in a range crest. Within the present study area the air flow thus reconstructed is from SE towards NW.

Possibly with the exception of the air flow observations derived from coastal sand dunes, all air flow directions in figure 9 are thought to depict the dominant air flow during at least authumn, winter and spring, as air temperatures at the glaciers then are well below 0°C and new snow is at hand in large quantity.

Observations on upper-air meteorological conditions (DMI 1967, 1977) at Egedesminde/Aasiaat, 65 km SE of southern Disko (Fig. 1), lend support to this supposition. Figure 10 shows radiosonde data on resultat wind directions and -speeds for the period 1956-70 at Egedesminde for surface level (27m asl.) and the 850 mb level (usually 1150-1450 m asl.) soundings. At the ground surface, the resultant wind is from NE and E in October-February, while winds with westerly component dominate during the summer. This corresponds well with the observations from Godhavn mentioned earlier in the paper. At the 850 mb level, however, the air flow is primarily meridional from S during the whole year, with maximum southerly component from January to June. Mean monthly velocities are often in excess of 20 knots. The zonal flow from E close to sea level is probably the result of the katabatic flow of cold air off the Greenland Ice Sheet from the almost permanent surface inversion, caused by strong radiational effects. During summer, this outflow is interrupted in the coastal areas by advection of warm and moist air masses from S and SW along the Davis Strait. High above sea level, the meridional flow from S at the 850 mb level however persist on a year-round basis, which is in accordance with the recurrent suggestion that the atmospheric circulation in the Greenland area includes a substantial meridional component (see e.g. Putnins 1970).

From this I would therefore suggest that many glacierzed mountains on Disko penetrates into the upper-air circulation system, and are for most of the year therefor exposed to fairly strong meridional winds from southerly directions. Below, terrain is mostly exposed to zonal winds from easterly and westerly directins as outlined above.

The air flow pattern displayed by figure 9 is not in perfect alignment to that observed at the 850 mb level at Egedesminde (Fig. 10), but this may well be the result of the meridional air flow being deflected somewhat against NW by the 1500-2100 m high mountains in interior Disko and in the peninsula Nugssuaq NE of Disko (Fig. 1). Within the present study area, this deflection around Disko result in the dominant wind direction being towards NW across the mountain tops. On the other hand, wind directions as indicated by the coastal sand dunes (Fig. 9) are in accordance with the zonal air flow pattern near sea level.

Summing up, the above considerations clearly point toward the potential importance of high-level snow drift from SE towards NW for the distribution of snow in the uppermost mountain areas in Disko. Not the least, this must obviously be of some influence for the mass-balance characteristics for high-lying glaciers within the study area, also. The very existence of large-scale niveo-eolian surface forms on most high-lying glaciers in Disko (Fig. 8) bears testimony to this conjecture.

SNOW DRIFT AND DIFFERENTIAL EQUILIBRIUM LINE DISPLACEMENT

Snow drift from SE appears to be frequent across the high areas within the study area (Fig. 9). To investigate the potential control of this feature on the observed equilibrium line displacements since the Little Ice Age, ΔELA values have been plotted against the potential snow drift upland size, measured towards SE from the top of the headvall or (for ice caps) from the ice margin, across onbroken, unglacierized and smooth terrain liable to experience extensive snow drift from SE.

Extensive high-altitude surfaces suitable for snow drift from SE are frequently found within the southern part of the study area, while the more alpine northern subarea is characterized by lesser values, only. Within this region high-level potential SE snow drift surfaces usually measure less than 300-500 m across. The results are depicted in figure 7c.

Figure 7c displays a rather interesting pattern. For potential high-level snow drift from SE across unglacierized surfaces measuring less than 500 m NW-SE, all ΔELAs are 50 m or less. For snow drift surfaces measuring more than 500 m across, ΔELA values are very scattered with a spread from 20 m to 220 m. In general, however, mean ΔELAs grow as the potential snow drift upland area increases. This lend support to the above hypothesis advocating the importance of snow drift as an explanation of the very different ΔELA values.

Ignoring all ice bodies with a potential SE snow drift upland area measuring less than 500 m NW-SE, and drawing isolines for the present minimum ELA (Fig. 7c), a consistent pattern emerges within the dispersed part of the diagram. High ΔELA values are seen to be associated both with high present ELAs and large potential snow drift upland areas. For potential snow drift uplands exceeding a certain critical value – about 1000 m in length – the present ELA however alone apears to be in control of the ΔELA.

A potential high-level SE snow drift surface measuring at least 500 m NW-SE thus appears to represent a controlling feature for ice bodies within the study area. Ice bodies characterized by a potential snow drift upland less than 500 m in length all display ELAs below 50 m since the Littel Ice Age, even though there may still be recognized a weak tendency towards greater ΔELAs for succesively greater potential snow drift distances for this group also. In other words, for this group of glaciers and firn areas the

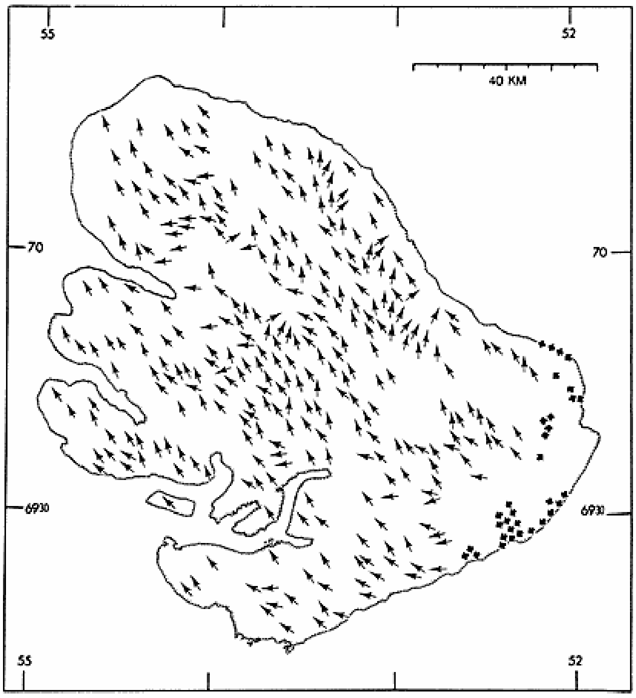

Fig. 9. Reconstructed dominant air flow pattern according to large-scale snow drift forms on glaciers (large arrows), and coastal sand dunes (short arrows).

Fig. 9. Dominerende vindretninger over Disko ifølge store snedriveformer på gletschere (store pile), og ifølge kystklitter (korte pile).

rise of the equilibrium line altitude appears to be relatively constant regardless of the general altitude of the glacier (as indicated by the current ELA). This is probably because snow drift for small snow drift uplands as these is of comparativly little importance only, and that the ΔELA in these cases primarily is controlled by other factors as e.g. changing air temperatures.

For potential snow drift uplands measuring more than 500 m SE-NW the spread of ΔELAs is considerable. But in general, the higher above sea level the glacier considered is situated, the greater is the corresponding rise in equilibrium line since the Little Ice Age.

Together, these observations point toward the general importance of snow drift from SE, and especially so for glaciers situated high above sea level. Only glaciers with a present mean ELA above 750-800 m asl. display above »normal« (50 m) ΔELA values. This is in good accordance with the information gained from radio-sonde data on upper-air meteorological conditions as presented above, and lends support to the supposition that the mountains on Disko penetrates into the meridional air flow system recorded at the 850 mb level (Fig. 10). It thus appears that the mass-balance for several of the high-level ice bodies within the study area extensively is controlled by snow drift set up by this meridional air flow.

The above considerations also offers an explanation of a somewhat curious feature appearing in figure 5c. It is immediately intelligible why only cirque- and valley-glaciers with a northwesterly aspect are associated large ΔELAs due to the snow drift from SE, but less so why several ice cap glaciers display high ELAs regardless of aspect? In this context it is important to bear in mind that ice caps typically are located on exposed mountain plateaus, and that snow drift from SE would supply snow to all radiating sectors of an ice cap, regardless of their individual aspect. Actually, the overall surface geometry of most ice caps within Disko tend to be elongated parallel to the air flow direction shown in figure 9, and they should probably be perceived as extraordinary large snow drift accumulation forms. Figure 5c thus is in accordance with what should be expected, provided the existence of important high-altitude snow drift from SE.

PALAEOCLIMATIC IMPLICATIONS

Provided that the mass-balance of high-lying ice bodies with northwesterly aspect among other things is controlled by high-level snow drift from SE, certain palaeoclimatic implications may be attempted.

Ignoring ice caps, high-lying ice bodies with northwesterly aspect have experienced an above »normal« (in ex-

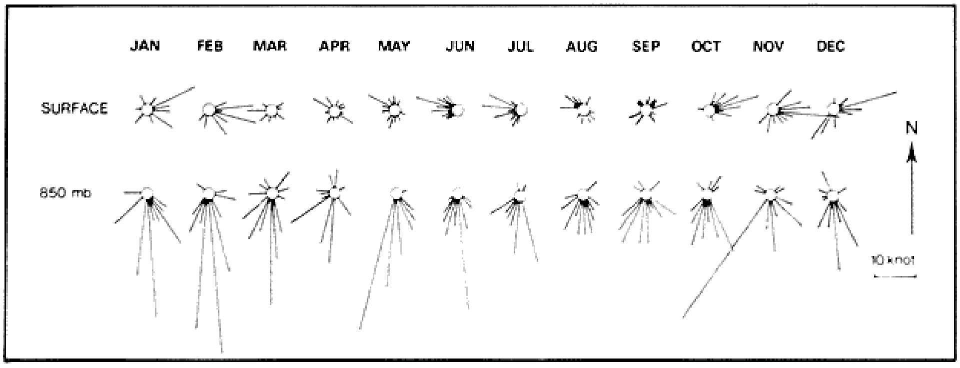

Fig. 10. Radiosonde data on resultant wind directions and -speeds at/above Egedesminde 1956-70.

Fig. 10. Resulterende vindretninger og -hastigheder ved og over Egedesminde ifølge radiosonde data 1956-70.

cess of 50 m) rise of the equilibrium line since the end of the Little Ice Age. Several glaciers within this group display ΔELAs of 100 m or even more. Meteorological observations carried out at Jakobshavn/Illulissat since 1873 (at sea level) indicate a mean air temperature rise of about 2°C and a rise in the yearly precipitation of about 20% since the end of the Little Ice Age (ending about 1895 AD.). This climatic change must influenze upon all ice bodies within the area, regardless of the size of their potential snow drift upland. Very great ΔELAs (reduced by a normal/background ΔELA of 20-50 m) must then in all likelihood be ascribed primarily to a reduced importance of high-level snow drift from SE since then. As the mean precipitation has gone up during the intervening period, a reduced snow drift influence would most likely be caused by a less intensive meridional high-level air flow over Disko nowadays, compared to what was normal during the Little Ice Age. On the other hand, the »background« ΔELA of 20 to 50 m characterizing ice bodies without significant high-level snow drift upland is then probably the result of changes in other meteorological factors as temperature, precipitaion, mean cloud cover/net radiation since the end of the Little Ice Age.

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Ice-wedge casts in an early deglaciated area of southern Sweden

Harald Svensson

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In a locality in northwestern Scania, an area that was the first part of Sweden to emerge from the Weichselian ice sheet, three types of ice-wedge casts are observed. The wedges are discussed from a morphogenetic, morphostratigraphic and chronological point of view.

Harald Svensson, professor, fil. dr. Geographical Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

Keywords: *Ice-wedge polygons, wedge-casts, segregated ice, fragipan, post-glacial transgression, Older Dryas, Younger Dryas.*

In a survey of relict ice-wedge polygons including reconnaissance flights and subsequent field check of crop marks in northwestern Scania (fig. 1), indications of polygon nets on the Bjäre peninsula were found to be rare (Svensson 1975). Only two small areas were registered as certain polygon sites (fig. 2), both located in cultivated fields at Vejby, at altitudes between 30 and 37 m a.s.l. This means they are situated below the Late Weichselian marine limit (55 m a.s.l.) but clearly above the maximum limit of the Post-glacial transgression of the area, 11-12 m a.s.l., (Daniel 1980).

In view of the wast areas of relict polygon patterns both to the northeast and southeast, the low frequency of polygon sites in the Bjäre peninsula is interesting in itself from a regional aspect. In addition, the Vejby area appeared to be important because of the possibilities for analysis of some types of ice-wedge pseudomorphs that were offered in a nearby gravel pit (Ljungby).

In this paper three types of ice-wedge casts will be discussed concerning morphogenesis, morphostratigraphy and chronology in relation to the deglaciation pattern of the area which probably was the first part of Sweden that was deglaciated.

ICE-WEDGE CASTS IN GLACIOFLUVIAL MATERIAL

In the eastern part of the gravel pit and in close connection to one of the polygon surfaces funnel-formed infillings of ice-wedge pseudomorphs showed up penetrating

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