Neoglacial Glaciations around Hans Tausen Iskappe, Peary Land, North Greenland

By Anker Weidick

Abstract

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All present glacier units in central Peary Land, North Greenland, have been systematically indexed in order to register existing documentation on glacier changes. The basis for this inventory work is the series of wide angle vertical aerial photographs flown in 1978 for Kort- og Matrikelstyrelsen. Determination of the glaciation limit on this base indicates a rise from 200 m a.s.l. at the outer coast of the Arctic Ocean to between 900 and >1000 m a.s.l. in the central areas of Peary Land. This trend is related to relatively higher precipitation and lower summer temperature at the outer coast compared to further inland.

The present glacier activity of individual glacier units has been investigated by study of all available aerial photographs from the years of 1950, 1960-63 and 1978. Locally photographic documentation can be extended back to 1938. In general, the glacier changes in this century have been very small, and significant changes are restricted to outlets of the Inland Ice, and to a minor degree outlets of local glaciers with mainly western and northern aspect.

Semi-permanent ice cover in the fjords leads to formation and retention of extensive floating lobes of glacier fronts. The climate of the 20th century appears to have been characterised by borderline conditions between periods of ice-free fjords and those of semi-permanent ice cover.

Neoglacial maximum is generally referred to A.D. 1900, with major thinning (downwasting) and recession in the first half of the 20th century, followed by slower recession, stand-still or even readvances during the last half of the century.

Keywords: Calf ice production, Glacier inventory, Glaciation limit, Neoglacial glaciations.

Anker Weidick, The Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400, Copenhagen NV, Denmark.

Introduction

This paper describes recent glaciological developments around Hans Tausen Iskappe, central North Greenland (Fig. 1), i.e. the development of the glacier cover since the Holocene climatic optimum (the Neoglacial, e.g. Kelly 1980), but with special emphasis on the events of the 20th century.

Due to the scattered information available and lack of place names for most glaciers, the first step was to establish a reference base for all glaciers in the region. This was undertaken following the recommendations of Müller *et al.* (1977), in the same way as that established for West Greenland by Weidick *et al.* (1992). This new reference system for eastern and central North Greenland has been used for recording glaciological and glacial geological information, and is employed in the text and illustrations of this paper. Supplementary inventory data, such as the areal extent of each glacier unit, is not given here.

Description of the high arctic glaciers of the region includes their response characteristics, and their relationship to older Holocene glacial events.

Geological setting

Geology and geomorphology

Topographically and geologically, eastern and central North Greenland can be divided into broad E-W trending zones (e.g. Bengaard & Henriksen 1984). From north to south these are:

1. An alpine and fjord-dissected zone of folded Cambrian formations in Johannes V. Jensen Land (Fig. 1) and islands to the west, i.e. north of Frederick E. Hyde Fjord and the outer parts of J.P. Koch Fjord. Isolated peaks reach to c. 2000 m and the area is characterised by the widespread occurence of valley glaciers.
2. A broad zone of high plateaus dominated by Silurian formations, bounded to the north by Frederick E. Hyde Fjord, and to the south by Independence Fjord and Wandel Dal. The highest peak reaches 1850 m, but the extensive plateau surfaces are at around 1000 m a.s.l. with ice caps and ice fields of different sizes; Hans Tausen Iskappe is the largest (Fig. 1). A correct delineation of Hans Tausen Iskappe is complicated by the fact that its two northern branches (Fig. 2) coalesce with local valley glaciers.
3. A southern zone made up of flat-lying Proterozoic formations extending southwards from the heads of Victoria Fjord and J.P. Koch Fjord in the west to south of Wandel Dal and Independence Fjord in the east (Fig. 1). The Inland Ice in the west part of the zone slopes down at a low angle to the ice-free land areas, which generally reach altitudes of 800-900 m a.s.l.

West of Hans Tausen Iskappe, between the heads of Victoria Fjord and J.P. Koch Fjord the northern local ice caps over Freuchen Land almost merge with the Inland Ice proper. This may provide an illustration of the early phases of the Holocene disintegration of the ice cover over the present coast land, leading to successive isolation of local ice caps from the ice sheet margins.

Climate

Climate records for the continental area of North Greenland are limited to Brønlundhus in Jørgen Brønlund Fjord, c. 100 km east of Hans Tausen Iskappe and cover the period 1948-50 (Fristrup 1961). January temperatures average –31°C, July +6°C and the annual mean temperature is –15°C. Precipitation is low at about 100 mm/year.

For Hans Tausen Iskappe the present precipitation (accumulation) at the southern dome is about 10 cm water equivalent/year whereas the northern domes receive slightly higher accumulation (Reeh 1995).

Measurements of accumulation on Chr. Erichsen Iskappe and on Heinrich Wild Iskappe (Fig. 3) c. 100 km northeast of Hans Tausen Iskappe in the period 1948-1950 (Høy 1970) are of the same extreme low order. Descriptions of all three ice caps witness to a rapid formation of superimposed ice in the firn. The temperature in 10 m depth on Chr.

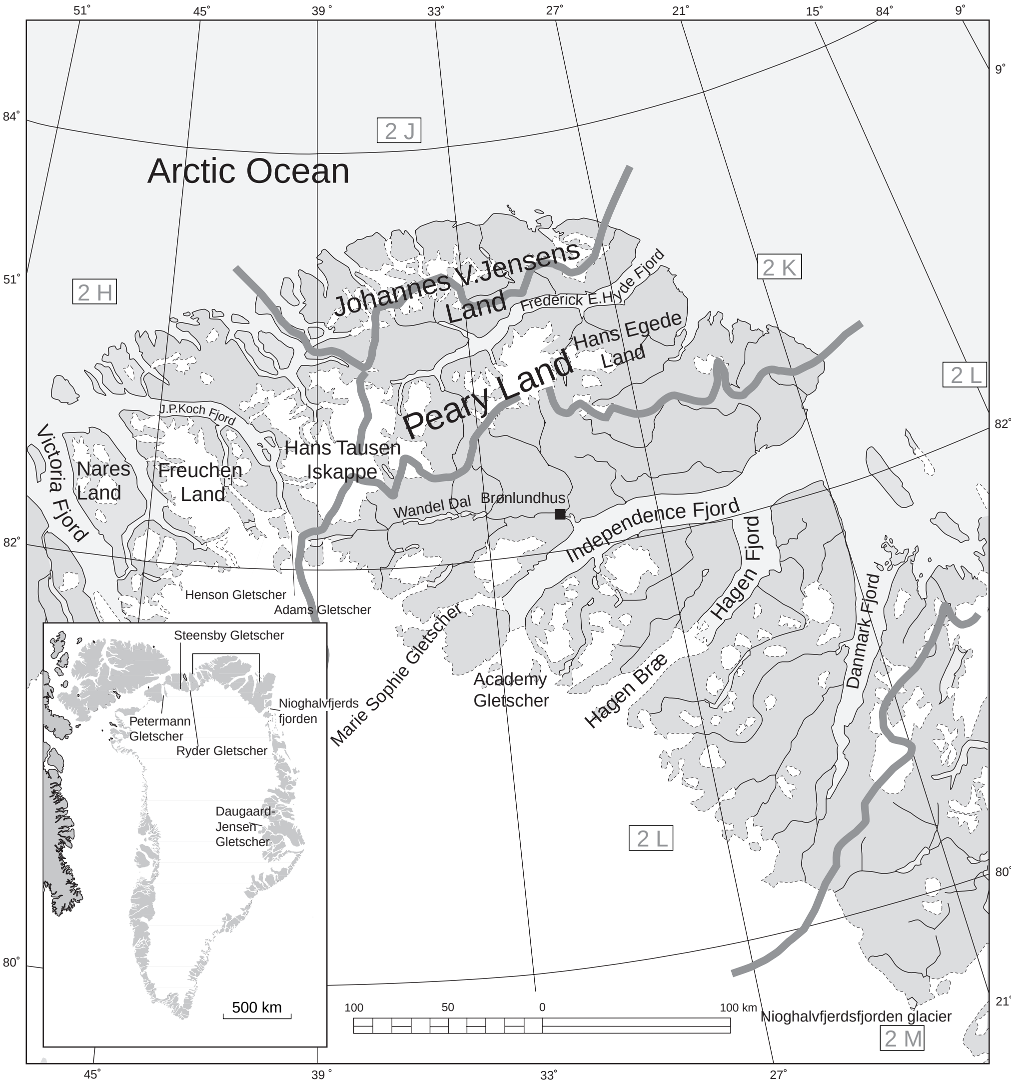


Fig. 1. Locality map for Peary Land and surroundings. On the map sheet water sheds dividing the area into the hydrological districts 2H to 2M are shown.

Erichsen Iskappe at 1000 m a.s.l. is given as –18°C, compatible with the figure of –20° to –17°C on Hans Tausen Iskappe at 1200 m a.s.l. (Reeh 1995).

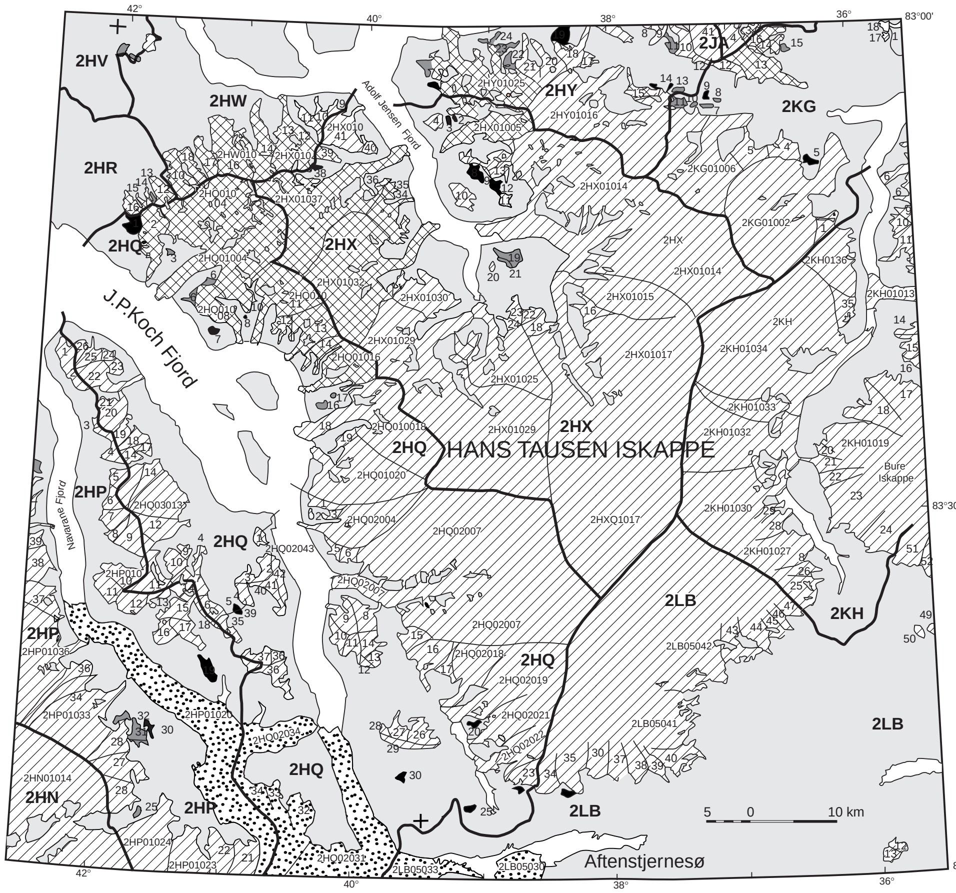
Davies (1972) divided northern Greenland into two distinct climatic zones: a subhumid zone along the coastal fringe, including the lower parts of Danmark Fjord and Independence Fjord, and an arid inland zone. Temperature conditions in both zones are nearly the same, but annual precipitation in the subhumid zone is up to 40 cm annually compared to only 10 cm/year for the inland arid zone.

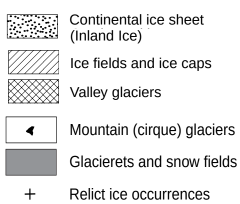
Present Glaciation, Fjords and Glacier Margins

Glaciation limit

In connection with the systematic registration of the glaciers of the area, an updating of the glaciation limit was made on the basis of the 1:100 000 orthophoto maps of Kort- og Matrikelstyrelsen (KMS, National Survey and Cadastre, Copenhagen). These maps were prepared using the series of vertical aerial photographs at 1:150 000 taken in 1978, and new fixed points surveyed throughout North Greenland. The

Fig. 2. Glacier division and glacier units in the Hans Tausen Iskappe area, together with the primary morphological classification of the individual glacier units.





map of glaciation limits is given in Fig. 4, and indicates generally the same trend of low coastal glaciation limit increasing inland towards the Inland Ice, as that published more than 70 years ago by Koch (1928). The new map gives maximum elevations (over 1000 m a.s.l.) around the mountains of Nordkronen west of Hans Tausen Iskappe, the area of greatest aridity.

The map also reflects that major sources of moisture must be from the open water areas among the pack ice and leads along coastal regions (Langway 1961, p. 1028), together with vapour transported by summer winds (Ohmura & Reeh 1991). The embayment of relatively low glaciation limit on the western flanks of Hans Tausen Iskappe seems to be influenced by the network of deeply incised fjords connecting the area with the Arctic Ocean.

The low level of the glaciation limit and widespread occurrence of valley glaciers in the coastal areas of eastern North Greenland imply a faster response of the glaciers to climate change than that of the large glaciers (ice caps) of central Peary Land around Hans Tausen Iskappe.

Fjords and calving outlets

The specific high arctic conditions of the glaciers of North Greenland, especially those draining from the Inland Ice to the heads of the fjords, are illustrated by strongly lobate or saw-tooth forms of the calving fronts floating in the fjords. Koch (1928) had attributed their preservation to the low surface slope (only minor crevasse development at the grounding line) and the constraining effect of the semi-permanent ice cover of the fjords in

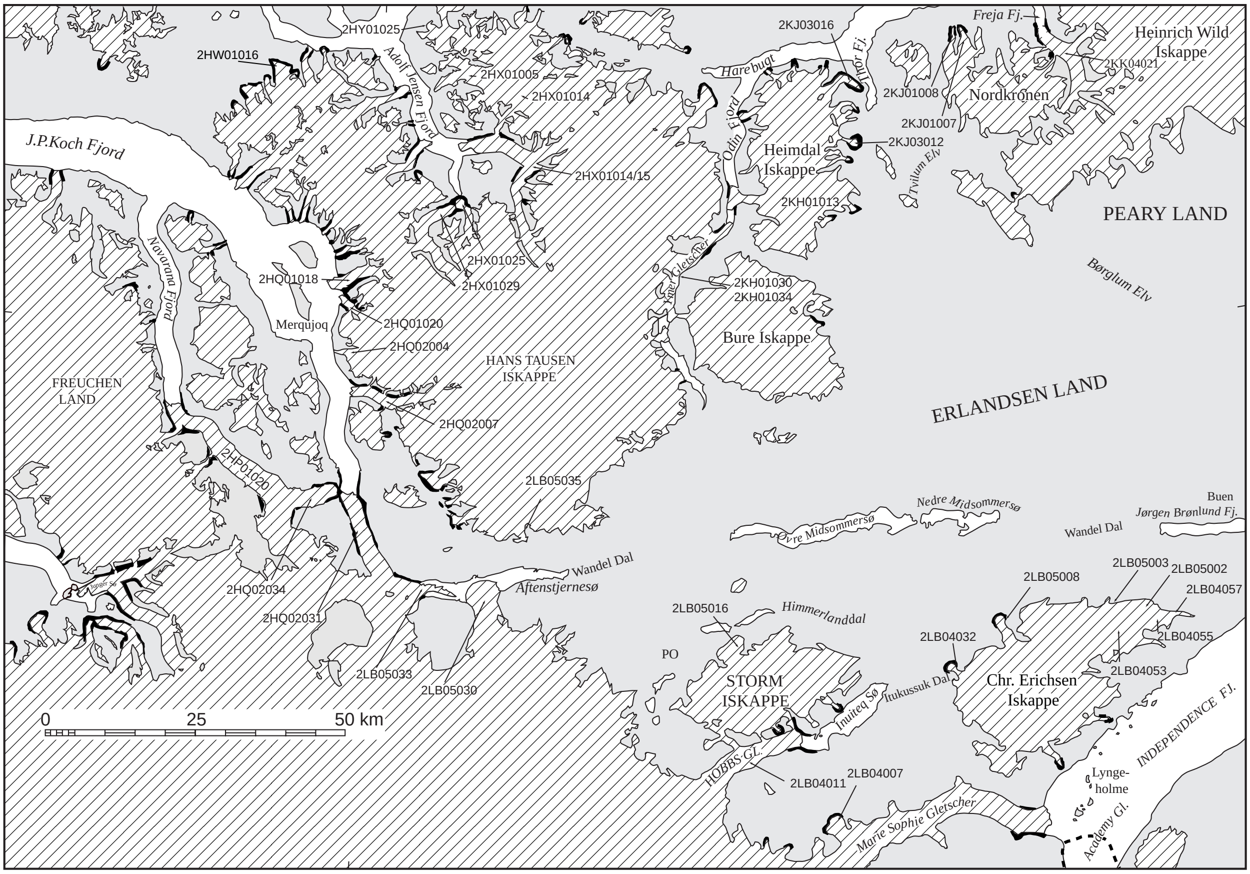


Fig. 3. Extension of neoglacial terrain around glaciers and ice caps in central Peary Land, shown with black colour. Glacier units described in the text are indicated by their location numbers.

front of the glaciers. Their changes and movement rate have been described by Higgins (1989, 1991), who also related the origin of Greenland ice islands to the infrequent break-up of large floating glaciers of this type. Several excellent examples of this type occur today north of 77°N on the east coast of Greenland (Reeh *et al.* 1999), of which the most intensively studied is the floating glacier filling Nioghalvfjerdsfjorden; this type of floating glacier is thus characterised as NFG-mode after the type locality of Nioghalvfjerdsfjorden glacier at 79°N. Essential characteristics of these NFG-mode outlets are:

1. They often have extending floating sections that partly or entirely fill the fjord.
2. Calving and dispersal of icebergs takes place on the rare occasions when the connected fjords are icefree; average calf ice production is low, compared to those of the more southerly outlets in East and West Greenland (see below).
3. Essential ice loss from the floating glacier outlets is not by calf ice production, but by bottom melting (Reeh *et al.* 1999), a consequence of thermohaline and tidal circulation under the floating ice.

By contrast, most calving glaciers south of 77°N are characterised by nearly rectilinear or concave frontal forms, and the front is usually located at or near the grounding line with often a nearly constant and high calf ice production. The calving glaciers of this type are referred to as the DJG-mode, after Daugaard-Jensen Gletscher at 72°N, East Greenland (Reeh & Olesen 1986; Reeh *et al.* 1999).

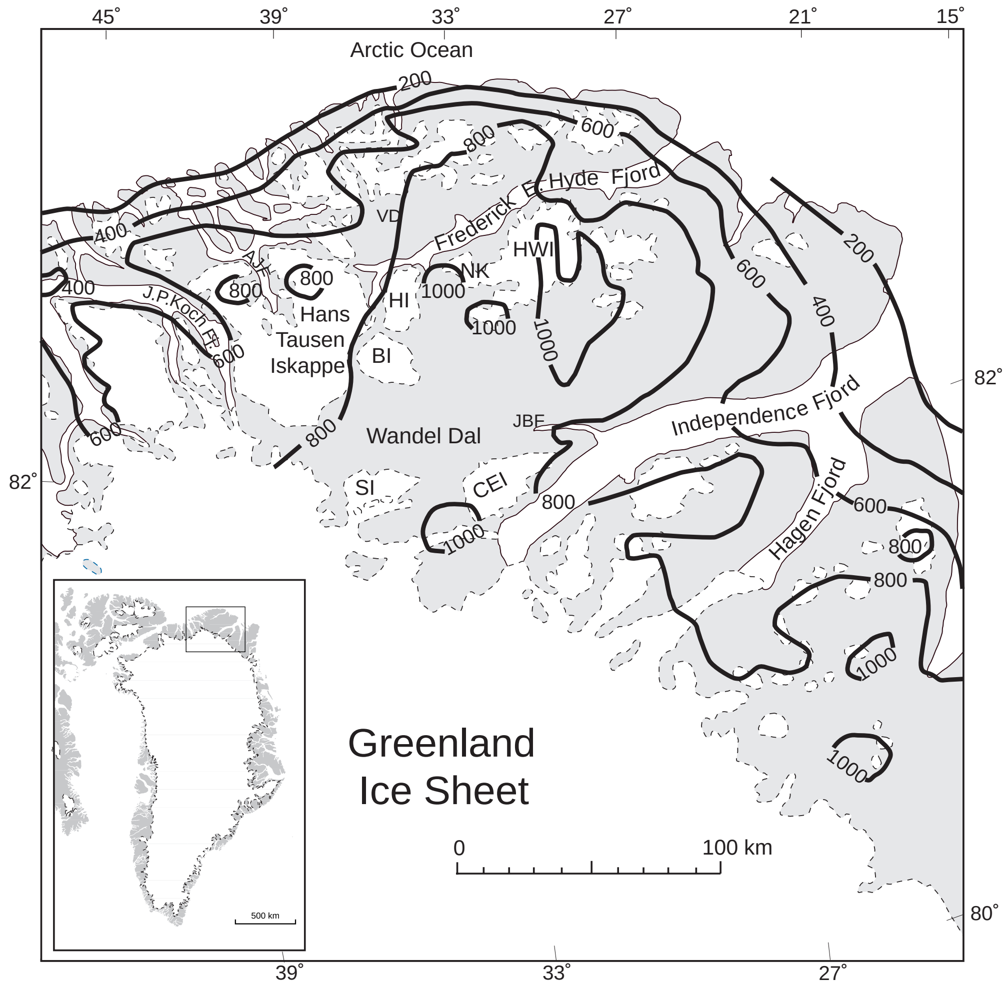


Fig. 4. Peary Land and surroundings. Altitude of glaciation limit in meter a.s.l. Abbreviations: AJF: Adolf Jensen Fjord, VD: Vølvedal, BI: Bure Iskappe, HI: Heimdal Iskappe, NK: Nordkronen, HWI: Heinrich Wild Iskappe, SI: Storm Iskappe and CEI: Chr. Erichsen Iskappe.

In Reeh *et al.* (1999) it is concluded that a slight temperature rise would be sufficient to cause a reduction of the present semi-permanent fjord ice in North Greenland, and induce a rapid disintegration of the floating glacier sections of North Greenland from the Inland Ice. However, the bathymetric and shifting hydrographic conditions of the different fjords and adjoining parts of the Arctic Ocean must also influence the changes of glacier fronts and ice coverage of the fjords.

^{14}C dates from the heads of North Greenland fjords (Bennike 1987; Kelly & Bennike 1992, Weidick *in* Landvik *et al.* 2001) show that during the early Holocene retreat, glaciers attained their present position as early as 8-9 cal. ka B.P. in wider fjord systems such as in Independence Fjord, whereas the outlets in narrow fjords such as in J.P. Koch Fjord first reached their present position at 6-7 cal. ka B.P. This reflects the importance of changes of hydrographic conditions and a relatively rapid glacier change in the larger fjord systems during the first phase of the Holocene deglaciation. Deglaciation of narrow fjords, valleys and especially the coastal uplands must then be regarded as later phases in the deglaciation.

The occurrence of both NFG-mode for most North Greenland glaciers and DJG-mode at the glaciers at the head of Independence Fjord, eastern North Greenland in this century may imply that present climatic conditions are intermediate between the two modes in the area. Possibilities for observing the change between the two modes therefore should be present. Unfortunately, aerial photograph coverage for the region is very limited, and searches of other historical material (old diaries, photographs) would be extremely time consuming. However, a single example of recent change between the two frontal modes is found at the head of J.P. Koch Fjord at Adams Gletscher (2HQ02031, Fig. 5).

The calving outlets from local glaciers into the ice covered fjords in the western and central parts of the Hans Tausen Iskappe area also generally show an

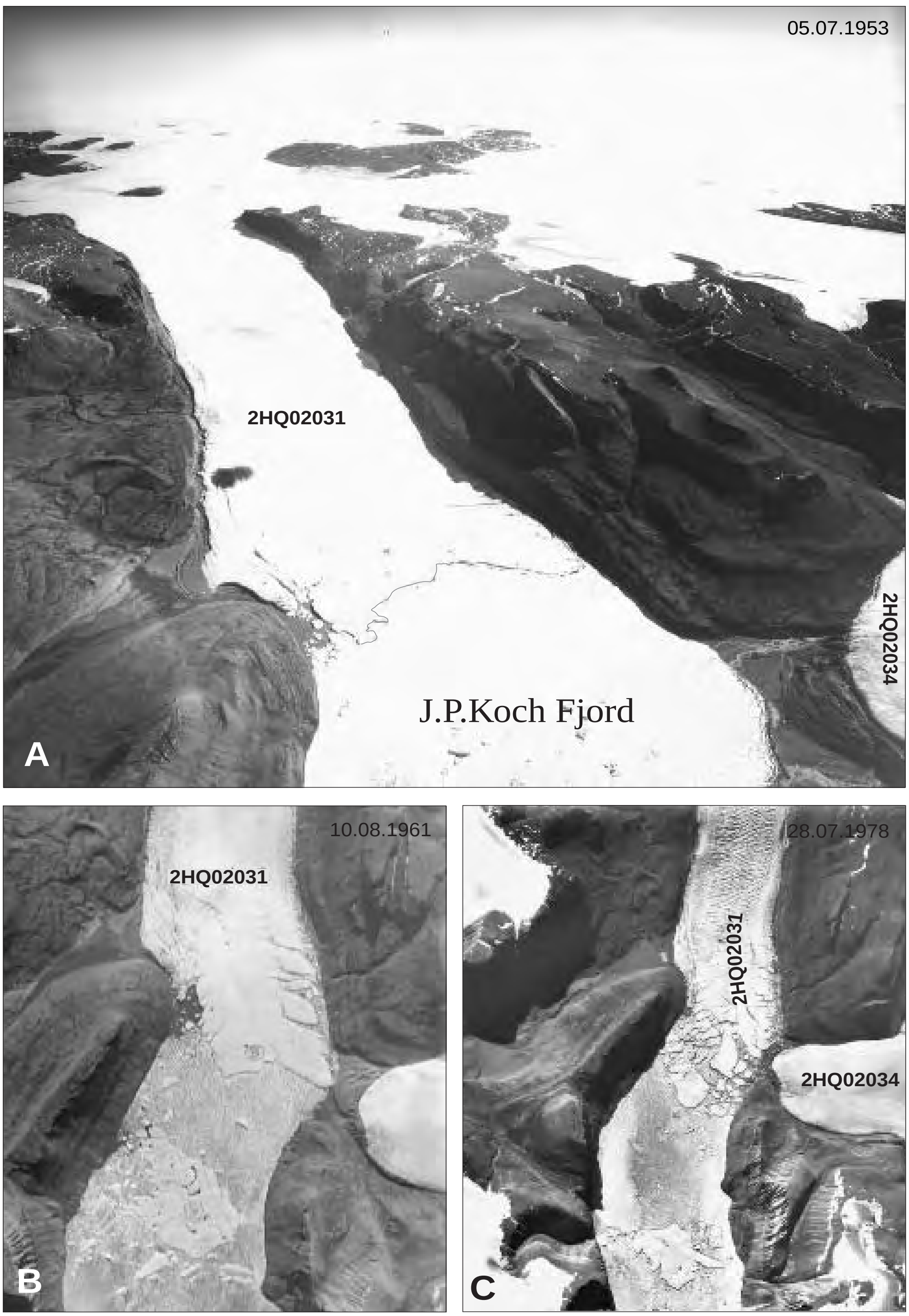


Fig. 5. Documentation of the changes of Adams Gletscher (2HQ02031), and Henson Gletscher (2HQ02034).

A: Photograph of July 5th, 1953, KMS route D-SØ, no. 1165.

B: Photograph of August 10th, 1961, KMS route 256H, no. 754

C: Photograph of July 28th 1978, KMS route 874F, no.2200

Copyright Kort- og Matrikelstyrelsen. A indicates the front of 2HQ02031 in DJG mode with a nearly rectilinear or concave glacier front, whereas B and C show the same front in NFG mode with strongly lobate front extending out into the fjord.

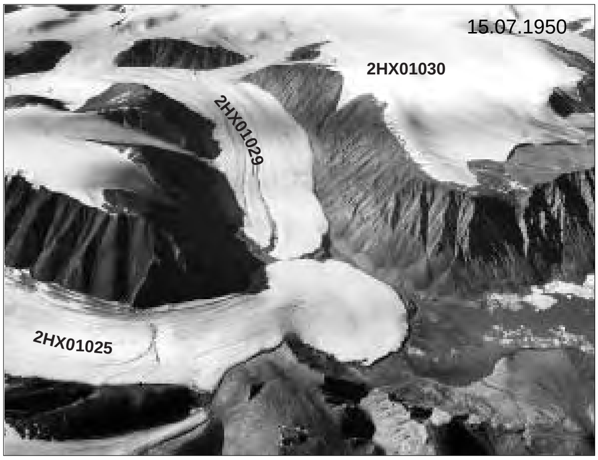


Fig. 6. Central parts of Hans Tausen Iskappe.

Left: Photograph, KMS route 547M-V, no. 10381 of July 15th 1950. The frontal parts of the two lobes of HX01025 and HX01029 almost reach the head of Adolf Jensen Fjord. At an altitude of c. 700 m a.s.l. the ice margin of sector 2HX01030 can be seen ending in an ice cliff, characteristic for many high arctic glaciers. Copyright: Kort- og Matrikelstyrelsen (KMS).

Right: Photograph KMS route 874E, no. 1121 of July 23rd 1978. The fronts of the two outlets of 2HX01025 and 2HX01029 are in almost the same position as in 1950 (a slight expansion has possibly occurred). The typical high arctic calving fronts of 2HX01014 and 2HX01032 are seen surrounded by semi-permanent fjord-ice. At the border between 2HX01014 and 2HX01015, strongly folded moraines are seen. Copyright: Kort- og Matrikelstyrelsen.

NFG-mode (see examples in Fig. 6, glaciers 2HX01014 and 2HX01032) whereas this is not the case in the eastern parts of the area around Frederick E. Hyde Fjord.

Land-based ice margins and glacier fronts

Land-based ice margins and glacier fronts also show characteristic high arctic features such as marginal superimposed ice or fringing glaciers, ice cliffs and steep ramps (Nobles 1961). At higher altitudes, ice cliffs (Goldthwait 1971) are usually well developed. An example from the central part of Hans Tausen Iskappe (glacier 2HX01030) is shown in Fig. 6 and here, as well as at lower altitudes, shear moraines in the fronts may indicate formation of superimposed ice. Another example from the area is glacier 2HW01016 at the northwestern section of Hans Tausen Iskappe, the location of which is shown in Fig. 3. However, the connection between the marginal forms and advancing or retreating ice in the high Arctic is still uncertain (e.g. see discussion on ice cliffs in Goldthwait 1961, p. 114 and Hooke 1970, p. 322) so they cannot be used as indicators of advance or retreat of ice margins.

Another specific form frequently seen is the piedmont glacier or expanded foot glacier. A characteristic and well developed form from Nares Land west of the entrance to J.P.Koch Fjord is shown in Weidick (1995, Fig. 36). Other examples from the study area are the glaciers 2HX01015 and 2HX01025 (Fig. 6). In places frontal reduction of such glaciers has taken place, e.g. glacier 2KJ03012 from Heimdal Iskappe, the position of which is shown in Fig. 3. The glacier outlet 2LB04032 (Elefantfoden) from the north-western part of Chr. Erichsen Iskappe (Fig. 3) was stable between 1950 and 1978 (1950: 548G-V no. 10220; 1978: 874J no. 2966 and 874K no. 921) and showed very slight recession since the neoglacial maximum, whereas the outlet of glacier 2HX01025 in central parts of Hans Tausen Iskappe at the head of Adolf Jensen Fjord (Figs 2, 3, 6) appears to have had a slight expansion between 1950 and 1978 by provisional estimate.

Location and Definition of the Present Ice Cover

The systematic registration of the glaciers on the map of Fig. 2 was carried out on the basis of studies of the 1978 vertical aerial photographs with respect to location, type and frontal conditions. For comparison, these observations were supplemented by scattered investigations of glaciers between Hans Tausen Iskappe and Hans Egede Land (Fig. 1), i.e. the area covered by Fig. 3.

The distribution of glacier types around Hans Tausen Iskappe is shown in Fig. 2. Of the 303 glacier units distinguished, 61 constitute Hans Tausen Iskappe proper and another 50 units make up two northern extensions of this ice cap, with a gradual change from ice cap sectors through ice fields to valley glaciers; the entire Hans Tausen Iskappe complex thus comprises 111 units.

Comments on the individual types of glaciers are given below.

The continental ice sheet margin (Inland Ice)

The part of the Inland Ice represented in Fig. 2 is divided into 9 units; the western parts form glacier sector 2HP01020 (Navaraneq Gletscher), and the eastern parts 2LB05030 (Astrup Bræ), which debouches into Aftenstjernesø (lake, surface 300 m a.s.l.).

The upland gradation from ice margin over snow patches to bare rock is only seen above 700 m a.s.l. Land-based outlets below this altitude usually have ice cliffs or ice ramps (Nobles 1961), with lacking or very narrow trim lines or Neoglacial moraine terrain such as at 2HQ02034 (Henson Gletscher).

Two floating glacier outlets of very different form occur in Aftenstjernesø. Glacier 2LB05033 is a perfect example of a saw-tooth glacier, typical of high arctic floating glaciers, whereas the eastern outlet of 2LB05030 (Astrup Bræ), exhibits a typical piedmont lobe (Fig. 7, 10). Bathymetric conditions in Aftenstjernesø are unknown; presumably the lake is deepest at its west end (towards the drainage outlet to J.P. Koch Fjord) so that only the damming lobes of 2LB05033 are floating whereas 2LB05030 is grounded. The extent of these lobes and the location of detached icebergs in aerial photographs from 1961 and 1978 suggests little ice movement.

For the major outlet which reaches the sea, 2HQ02031 (Adams Gletscher), the movement has been estimated at 170 m/year (Higgins 1991). This outlet is surrounded by neoglacial moraines and trim line zones that extend c. 3 km north of the 1978 frontal plain.

Ice fields

Ice fields are defined by Müller *et al.* (1977) as masses of sheet or blanket types of ice, whose thicknesses are not sufficient to obscure the subsurface topography. They are here viewed as transitional between ice caps and valley glaciers; their frontal characteristics correspond to those of ice caps (see below) and they are grouped with ice caps on Fig. 2. The units corresponding to this type are found in the northern parts of the Hans Tausen Iskappe complex.

Fig. 7. South-east corner of Hans Tausen Iskappe showing the lake of Aftenstjernesø with the fronts of glaciers 2LB05033 and 2LB05030 (Astrup Bræ). Parts of J.P.Koch Fjord show the floating Inland Ice outlet of Adams Gletscher (2HQ02031). The front of Adams Gletscher is surrounded by neoglacial moraines extending c. 4 km beyond the glacier front on this 1978 aerial photograph.

The cirque glaciers of 2HQ02025, 2HQ02030 and the frontal cirque tributary to outlet 2LB05035 illustrate different degrees of down wasting.

Locations of radiocarbon dated organic material (Ua-4586, Ua-4587, GSC-2279 and I-9130) indicate a retraced position of glacier lobe 2HQ02031 from c. 6000 years ago and up to the Little Ice Age (cf. Landvik et al. 2001). KMS route 874G, no. 2230 of July 28th 1978. Copyright, Kort- og Matrikelstyrelsen.

Ice caps

Ice caps are the dominant ice type of the area. The largest is Hans Tausen Iskappe and Table 1 shows the size of Hans Tausen Iskappe compared to other local ice caps of the region.

Land-based glacier outlets are often surrounded by narrow trim line zones or by neoglacial moraines, in particular around small outlets which descend steeply from ice caps, and around some of the floating outlets in the northern and western parts of the Hans Tausen Iskappe complex (Fig. 3). The most important floating outlets are here typically characterised by protruding fronts of calf ice assemblages but these are also bordered by trim lines or fresh moraines indicating a net thinning in most recent time.

For the largest outlets of Hans Tausen Iskappe complex, Higgins (1991) measured rates of movement varying from 175 m (2HQ02007) to 30 m (2HQ01016) annually for the west and north sides of the ice cap complex. However, while Higgins (1991) stated that the large eastern outlet from Hans Tausen Iskappe: 2KH01034 (Ymer Gletscher) had insignificant movement, stake movements in connection with mass balance measurements in 1994/95 in the nor-

Table 1. Estimated areas and volumes of ice caps in Peary Land.

Ice cap	Area	Thickness	Volume (ice)
Hans Tausen	4208 sq.km (a)	175 m	736 cubic km (b)
Heinrich Wild	1042 sq.km (a)	100 m	104 cubic km (b)
Chr. Erichsen	529 sq.km (a)	80 m	42 cubic km (b)
Bure	397 sq.km (a)	80 m	32 cubic km (b)
Heimdal	368 sq.km (a)	80 m	29 cubic km (b)
Storm	300 sq.km (a)	80 m	24 cubic km (b)

(a) Area according to W. Starzer (personal communication).

(b) According to Cailleux et Lagarec (1977) as related mean glacier thickness to glacier size. Measured volume of Hans Tausen iskappe complex with the area figure of 4208 sq.km is calculated to relate a volume of 761 cubic km on the basis of radar measurements by Gundestrup et al. (W. Starzer, pers. Communication).

thern part of the ice cap (2KG01002, Fig. 2) showed the maximum rate of movement at the equilibrium line is about 50 m/year, declining to 5 m/year at the land-based glacier terminus (Reeh 1995).

Valley glaciers

Valley glaciers are mainly found in the north-western part of the area (Fig. 2). In their lower parts they are often surrounded by well developed trim line zones and moraines, indicative of net recession.

Cirque glaciers

The group was originally termed mountain glaciers (Müller *et al*. 1977), i.e. small glaciers of any shape, sometimes similar to a valley glacier, but much smaller; frequently located in cirque or niche. Most of those in the study area here could be described as cirque glaciers. The cirque glaciers occur scattered throughout the upland areas of otherwise ice-free terrain. The few (cf. Fig. 2) registered cirque (mountain) glaciers have little frontal development of neoglacial moraines, such as are known from other parts of the world. In place of recessive features they show a state of general waning or downwasting, with dust covered surfaces such as 2HQ02025 and 2HQ02030 on Fig. 2 and 7. Examples of "fossil" glaciers of this type have been observed on aerial photographs, where the glaciers can scarcely be distinguished from the surrounding land (depicted in Fig. 2 as "relict ice occurrences").

Glacierets and ice fields

Glacierets and ice fields are defined by Müller *et al*. (1977) as a small ice mass of indefinite form in hollows, river beds and protected slopes. They occur frequently throughout the area. Their mergence with other glacier forms, especially at the eastern and southern margins of Hans Tausen Iskappe and at the Inland Ice margin, makes delineation and differentiation of these ice cover types difficult.

General trends of the ice cover of the area

The general trends of the ice cover are summarised in the map of Fig 3, which shows the extent to which the glaciers were surrounded by fresh Neoglacial moraines or trim line zones in 1978, indicative of recent net recession.

The recession is in general related to larger outlets from ice caps and valley glaciers, and in particular to western and northern facing examples. Usually the net recession is modest, of the order of tens to hundreds of metres since the neoglacial maximum. One extreme exception on the map of Fig. 3 is the outlet of 2HQ02031 (Adams Gletscher) from the Inland Ice, which shows a net retreat of *c*. 3 km.

The permanence of the upland cirque glaciers may indicate positive mass balance for most recent decades, but this is contradicted by the occurrences of relict ice. In this context it is possible that downwasting rather than recession is characteristic for the upper reaches of the region. This process has been described for the western parts of North Greenland by Davies & Krinsley (1962; Brother John Gletscher, p. 124). In respect of the Holocene recession of the ice cover over North Greenland the same process is described by Kelly & Bennike (1992, p. 19). Low slope of the subsurface, relatively small thickness of the ice cover, confinement of the glaciers to narrow valleys and the low temperatures in the glacier body with extensive freezing of the glacier to the subsurface, may favour conditions for downwasting and relict ice formation.

Historically Documented Glacier Activity in Peary Land

The presentation of Neoglacial terrain around the glaciers in Peary Land (Fig. 3) can only give an impression of recent net recession of the glacier cover over specific areas, a recession which may be compensated by advances or readvances of other areas.

Earlier glaciological investigations of the area

Recent glacier changes in North Greenland were investigated by Davies & Krinsley (1962) and on the basis of conditions in the period 1956-1960 they concluded for Peary Land that "of the 309 glacier fronts in the area, 208 are apparently stable, 99 show definite indications of recent retreat and 2 show evidence of recent advance. Of 11 small isolated ice caps, 9 are apparently stable and 2 show sign of recent retreat" (Davies & Krinsley 1962, p. 127). Their investigations covered the entire area of Peary Land north of Independence Fjord and east of J.P. Koch Fjord, but the location of the observed glaciers is not given in most cases and it is therefore not possible to update the observations given.

Early glaciological work on the ice caps of the region is reported by Høy (1970). Mass balance measurements on Chr. Erichsen Iskappe were initiated by B. Fristrup and Th. Høy in 1948-49, continued in 1951 and 1952, and terminated with a re-survey in 1963. Høy (1970) records an accumulation figure of 10-12 cm water equivalent per year, and a marginal net recession of the north-eastern ice margin, around the sectors 2LB05002 and 2LB05003 in Fig. 3, of 80-150 m in the period 1950-1963, i.e. 6-12 m/year at an altitude of c. 870 m a.s.l. Investigations on the south-eastern ice cap margin around sector 2LB04055 (Fig. 3), at near the same height showed no signs of change during this period. As a follow-up of this observation a comparison of the conditions at this margin on aerial photographs of July 7th 1960 (route 256M no. 754) with aerial photographs for July 21st 1978 (route 874K no. 915) revealed little change of the ice margin position.

Present evaluation of glacier changes

The maximum age of the Neoglacial trim line zone mapped in Fig. 3 can only be documented for those glaciers in North and North-East Greenland where observations extend back to the beginning of the 20th century, i.e. Petermann Gletscher, Ryder Gletscher, Academy Gletscher and Hagen Bræ; fluctuations of these glaciers have been summarised by Davies & Krinsley (1962), Higgins

(1991) and Weidick (1995). On this evidence the oldest neoglacial moraines are considered to be *c.* 100 years old.

The documentation for subsequent glacier fluctuations during this century is very sparse. For the area of study regular observations began with the oblique photographs of 1938 (Koch 1940) and the oblique photographic routes of the Geodetic Institute, dating from the early 1950s, but without uniform coverage of the area. Full coverage by vertical aerial photography was first achieved in the early 1960s, and repeated by the high altitude wide-angle photography of 1978. Evaluation of the often small glacier changes is hindered even here by shadow positions of the glacier fronts and, for floating glacier tongues, the common gradation between glacier and floating calf ice of the glacier fronts.

Examples of fluctuations given below illustrate some trends in the behaviour of glaciers in the area.

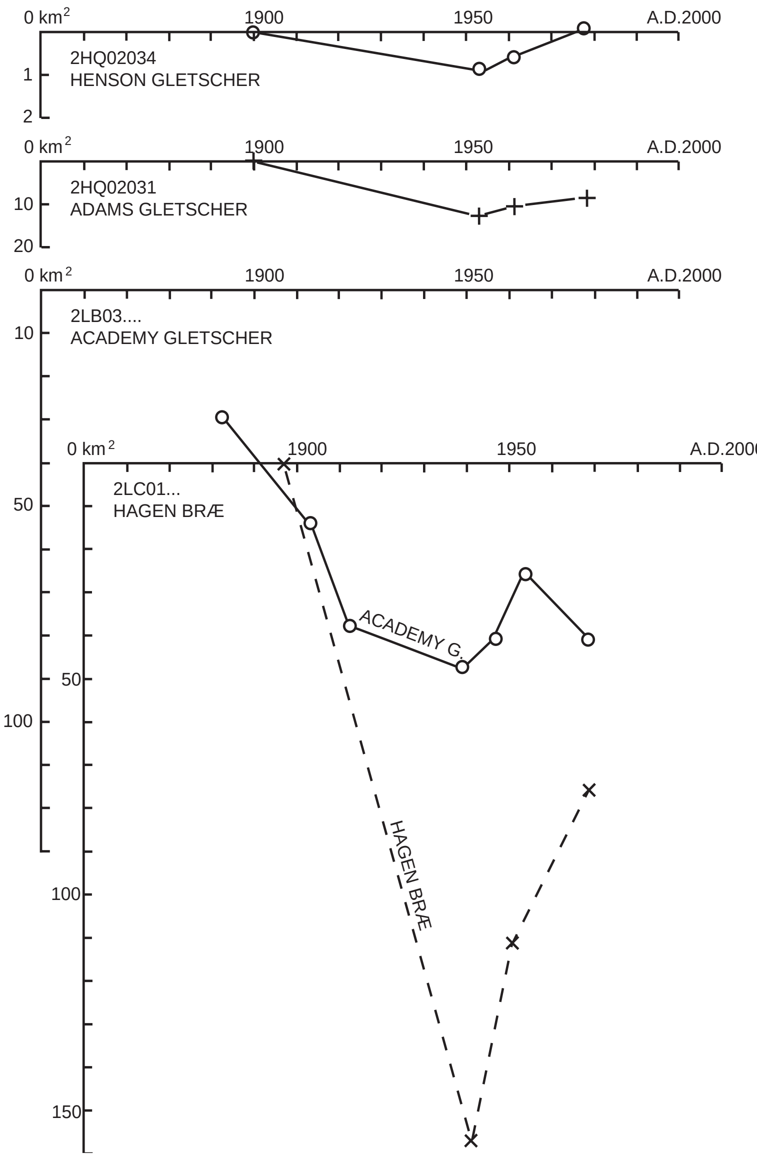


Fig. 8. Estimated changes of area of some Inland Ice outlets in eastern and central North Greenland. NB: The vertical scale for the land-based outlet Henson Gletscher (2HQ02034) differs from the scales of the floating outlets of Adams Gletscher, Academy Gletscher and Hagen Bræ.

Fluctuations of the Inland Ice margin

The largest extension of the Neoglacial trim line zone can be observed around the outlet of Adams Gletscher (2HQ02031), which debouches into the head of J.P. Koch Fjord and has a 2-3 km wide calving front. Since the neoglacial maximum extent (about 1900?) the glacier front has retreated by over 4 km and was observed in this retracted position in 1950; subsequently it gradually advanced by 1-2 km to its 1978 position. In Fig. 8 these changes are given as loss or gain in the glacier area, and the changes are here compared with those of other calving outlets of the Inland Ice in eastern North Greenland (Academy Gletscher and Hagen Bræ). With reservations for the scatter and scarcity of observations there seems to be the same general trend in the glacier behaviour. A major recession of the outlet glaciers in the first half of the 20th century is followed by minor readvances in the second half. Ryder Gletscher and Steensby Gletscher elsewhere in North Greenland seem to show similar trends (Higgins 1991) which can be linked to a period of break-up of the semi-permanent fjord ice corresponding with maximum temperatures for this century as revealed in the Hans Tausen Iskappe ice record (Hammer & Thomsen 1998).

The changes of the frontal positions of Adams Gletscher (Fig. 5) also appear to reflect a transformation of the glacier front from a DJG-mode in 1953 to an NFG-mode in 1963 and 1978.

The neighbouring land-based glacier 2HQ02034 (Henson Gletscher, cf . Figs 5, 8) also shows the same trend of recession prior to 1950 and the subsequent readvance, whereas other higher altitude outlets draining into the lake Aftenstjernesø (2LB05033; no name, and 2LB05030; Astrup Bræ, Fig. 7) show no change throughout the period 1950-1978.

Glacier changes 1938-1978 at outlets from ice fields, ice caps and valley glaciers

For most glacier outlets, the zones of trim line or Neoglacial moraines apparent on the 1950 series of aerial photographs show little subsequent change in their extension in the fjords, or their extension on land. Their main recession must therefore have been achieved prior to 1950. For example, the protruding glacier fronts on the west side of Hans Tausen Iskappe (Higgins 1991) show essentially the same configuration on the aerial photographs of the early 1950s and those of 1978.

The earliest photographs of some of the glacier lobes from April 15th 1938 are published in Koch (1940) and give only local and restricted information of the status of the glacier at that time. However, the age of the observations justify comments on the updating of glacier changes at these localities, as given below. The positions of these glaciers are shown in Fig. 3.

2KK04021 (Balder Gletscher)

This glacier is situated at the head of Freja Fjord, a southern minor tributary to Frederick E. Hyde Fjord. The glacier is the largest drainage outlet of Heinrich Wild Iskappe and terminated with a 1.5 km wide, "normal" calving front (DJG-mode) in 1978. Photographs of the glacier in 1938 and 1978 are shown in Fig. 9.

The glacier had presumably receded from its Neoglacial maximum *c*. 1.8 km north of its 1978 position before 1938 (cf. Fig. 9). The subsequent recession between 1938 and 1978 (route 874F, no. 281) is between 200 and 500 m.

2KJ01007 and 2KJ01008 (no names)

These outlets are lobes from the ice fields covering the mountain Wistar Bjerg (1850 m high). They descend down to altitudes of respectively 300 and 200 m. Their flanks are characterised by ice cliffs, and a trim line zone is apparently lacking or very narrow at the 1938 position. Only the front of 2KJ01007 can be observed on the 1938 photograph. Both glaciers were close to their Neoglacial maximum in 1938 and only a slight thinning of both glaciers took place in the period up to 1978 (route 874E no. 1105).

2KJ03016 (no name)

This glacier is an outlet from Heimdal Iskappe draining down to Thor Fjord, a southern tributary to Frederick E. Hyde Fjord. The lobe descends rather steeply in a narrow gorge down to the shore of Thor Fjord, where the front in 1938 (Koch 1940, fig. 49) formed a small piedmont. Subsequent thinning and disappearance of the front from the coastal plain occurred in the period up to 1978.

2KH01013 (no name)

This is a *c*. 1.5 km wide glacier outlet descending from Heimdal Iskappe (Fig. 3). Its front expands to a piedmont lobe which blocks Odin Fjord for more than 4 km. With some reservation it can be concluded that the front in 1938 may have had a position a little more retracted than that of 1978 (route 874F, no. 2188). In Koch (1940, fig. 50) the glacier illustrated is described as Ymer Gletscher, but Ymer Gletscher is in fact located farther to the south and cannot be seen on the 1938 photograph.

2HQ01018 and 2HQ01020 (no names)

Both glaciers are outlets from Hans

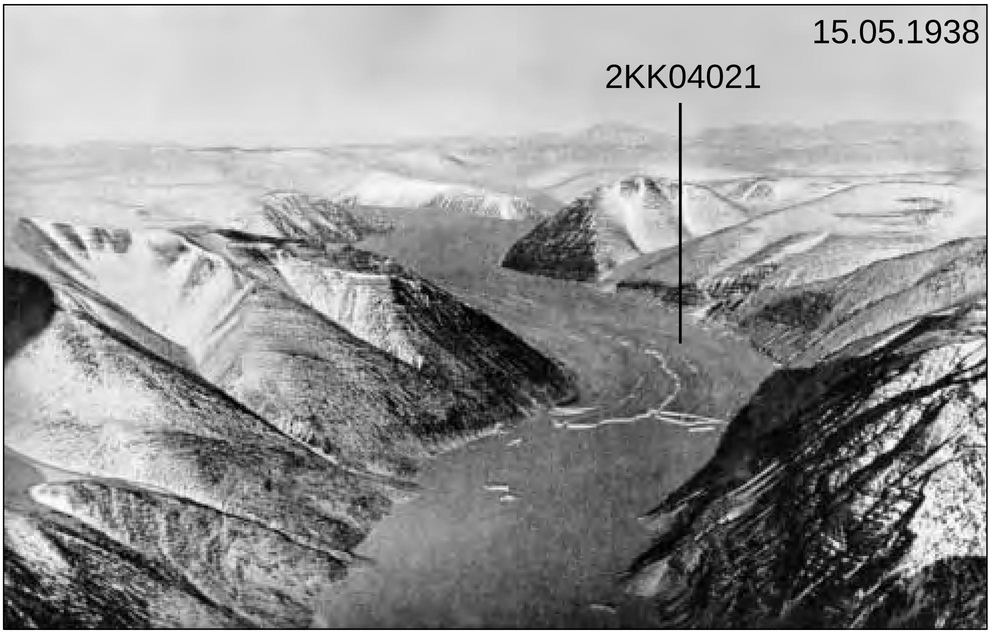


Fig. 9.
Top: Freja Fjord with Balder Gletscher (2KK04021) photographed May 15th 1938 (Koch 1940).
Bottom: Section of KMS 1:100 000 orthophoto map 82 Ø3, based on aerial photographs of 1978 (route 874E, no. 1105, July 23rd 1978). Copyright: Kort- og Matrikelstyrelsen.

Tausen Iskappe draining to J.P.Koch Fjord (Fig. 3). They descend at a moderate gradient to the fjord where their fronts appear as an assemblage of packed calf ice concentrations (Higgins 1991, Fig. 12) protruding *c*. 2 km out into the fjord. The frontal widths of the two outlets are 2.2 km (2HQ01018) and 1 km (2HQ01020) and their rates of movement are given by Higgins (1991) as 60 m/year and 70 m/year respectively.

On the 1938 photographs reproduced in Koch (1940, Figs 51-52) calf ice concentrations can also be seen reaching out into J.P.Koch Fjord from the neighbouring outlet 2HQ02004 (Fig. 3). All the concentrations of packed calf ice from the outlets into J.P.Koch Fjord have the same general extent on the photographs from 1938 and those of 1978 (route 874E, no. 1125). The well developed trim line zone on the 1978 photograph seems not so widely developed in 1938 where the features are veiled by a thin snow cover, and a thinning of the glaciers 2HQ01018 and 2HQ01020 in the period 1938-1978 must therefore be concluded.

2LB05016 (no name)

This is a 5 km wide piedmont glacier outlet on the northern side of Storm Iskappe, which descends from the firn area at *c*. 1000 m altitude down to the front at 500 m altitude. Precise determination of the frontal position in 1938 cannot be made due to the distant view of the glacier, but apparently little or no change had taken place up to 1978 (route 874J, no. 2971).

Glacier changes 1960-1978 at outlets from ice fields, ice caps and valley glaciers

Only the glaciers described above are covered by photographs back to 1938; many other glaciers are covered by information back to the oblique photographs of *c*. 1950, but the first regional coverage is by the vertical aerial photographs of 1960-63. A total of 33 glaciers can be evaluated in terms of their activity between 1960 and 1978.

The 33 glacier units are listed in Table 2 by their location number, name if any, geographical coordinates, lowest and highest parts of the glacier (highest part omitted for Inland Ice sectors or outlets), morphological code and main exposure directions.

The morphological code is described in the matrix form given in Table 3 (originally proposed by Müller *et al.* 1977), modified for Greenland by Weidick *et al.* (1992). Of the 33 glaciers listed in Table 2, 23 are related to ice fields, ice caps and valley glaciers (first digits 2, 3 and 5 in the morphological code Table 2), seven units are related to the Inland Ice (first digit 1) and three are cirque glaciers (first digit 6). For the 23 glaciers related to the ice fields, ice caps or valley glaciers, 16 are stationary or show slight retreat, and only one has slightly advanced in the decades since 1950. The reported cases of possible surges are very uncertain; they are based on the appearance of pitted glacier surfaces and/or strongly foliated moraines. In all cases there has been no change in the glaciers between 1950 and 1978, so surges have not been demonstrated. The glacier changes are in all cases small, which is the reason that the three remaining glacier units of ice fields, ice caps and valley glaciers are labelled "uncertain".

Specifically high arctic features such as ice cliffs generally occur in the higher reaches of the ice margin, but can also occur in lower frontal regions. Thus at glacier 2HWJ01016, located in Fig. 3, the recession given is a recession of superimposed ice deposited in front of the real glacier lobe.

Cirque glaciers

The few cirque glaciers (cf. the plots on the map Fig. 2) show generally little area change in the period 1950-1978. Isolation and slight thinning of a cirque glacier from the outlet of 2LB05035 on the south side of Hans Tausen Iskappe is shown here in Fig. 10. It will be noted that the reduction of the area of the cirque glacier between 1950 and 1978 is small.

Summary of the historical changes of glaciers in central Peary Land

Recent recessional features (neoglacial moraines, trim line zones) are plotted in a very generalised way in Fig. 3. For the land-based outlets, net recession for this century is usually confined to the fjord systems north and west of Hans Tausen

Location number and name	Coordinates		Elevation		Morphol.	Exposition	Reference to
	N	W	Low	Heigh	Code		figure in text
2HP01020 Navaranaq Gletscher	82°40'	48°25'	0	–	164112	NW	2, 3
2HQ01020 n.n.	82°32'	39°52'	0	1200	364312	NW	2, 3
2HQ02004 n.n.	82°29'	40°05'	0	1200	364210	W	2, 3
2HQ02007 n.n.	82°27'	39°00'	0	1250	364112	W	2, 3
2HQ02025 n.n.	82°12'	39°07'	550	750	633112	E	2, 7
2HQ02030 n.n.	82°14'	39°38'	650	750	633112	SW	2, 7
2HQ02031 Adams Gletscher	82°10'	39°49'	0	–	164114	N	2, 3, 5, 7, 8
2HQ02034 Henson Gletscher	82°16'	40°51'	20	–	163114	E	2, 3, 5, 8
2HW01016 n.n.	82°52'	41°11'	250	1350	523112	N	2, 3
2HX0l00S n.n.	82°54'	39°04'	50	1150	533114	W	2, 3
2HX01014Tjalfe Gl.	82°46'	38°19'	0	1350	324116	W	2, 3, 6
2HX01015 n.n.	82°44'	37°53'	100	1350	362216	NW	2, 3, 6
2HX01025 n.n.	82°39'	38°48'	10	1150	301213	N	2, 3, 6
2HX01029 Lurgletscher	82°39'	39°43'	50?	1200	323213	NE	2, 3, 6
2HY01025 n.n.	82°58'	39°00'	0	900	524110	N	2, 3
2KG01002 Hare Gl.	82°50'	36°27'	110	1250	323113	NE	2
2KH01013 n.n.	82°43'	35°32'	0	1250	362213	W	2, 3
2KH01030 n.n.	82°31'	36°53'	10?	1300	366116	NE	2, 3
2KH01034 Ymer Gl.	82°39'	36°54'	0?	1300	366110	NE	2, 3
2KJ01007 n.n.	82°55'	33°00'	300	1800	233112	N	3
2KJ01008 n.n.	82°54'	33°12'	200	1800	233112	N	3
2KJ03012 n.n.	82°48'	34°37'	100	1400	362212	E	3
2KJ03016 n.n.	82°51'	34°45'	200	1500	363212	E	3
2KK04021 Balder Gl	82°54'	31°45'	0	1500	364112	N	3, 9
2LB04011 Hobbs Gl.	81°49'	36°30'	150?	–	166113	NE	3
2LB04007 Marie Sophie Gletscher	81°40'	35°00'	0	–	164113	E	3
2LB04032 Elefantfoden	82°00'	33°30'	200	1200	361313	NW	3
2LB05008 Skjoldet	82°02'	33°00'	180	1200	361313	NW	3
2LB05016 n.n.	82°02'	35°58'	490	1051	362113	N	3
2LB05030Astrup Bræ	82°04'	38°34'	300	–	166113	N	2, 3, 7, 10
2LB05033 n.n.	82°07'	39°36'	300	–	166113	E	2, 3, 7
2LB05035a n.n.	82°14'	38°22'	480	1200	363112	SE	2, 3, 7, 10
2LB05035b n.n.	82°13'	38°21'	550	740	630112	E	2, 7, 10

2LB05035a: Main glacier
2LB05035b: Cirque glacier, now isolated from main glacier.

Table 2. Glacier activity – Central Peary Land.

Iskappe, and further south to the regions around inner Independence Fjord.

The map of Fig. 3 only reflects the distribution of a "neoglacial" formation, representing the maximum extension of the "Steensby stade" of Kelly & Bennike (1992), i.e. the culmination of the readvances of the local glaciers after the Holocene climatic optimum. This culmination is, by analogy with neighbouring areas, believed to have taken place at the end of the Little Ice Age, i.e. around A.D. 1900.

The borders of ice showing no recession in Fig. 3 mark a nearly stationary ice margin. The stability is in places documented by aerial photographs from 1938 to 1978, which show that the pre-

	Digit 1 Primary classification	Digit 2 Form	Digit 3 Frontal characteristics	Digit 4 Longitudinal profile	Digit 5 Major source of nourishment	Digit 6 Activity of tongue
0	uncertain or miscellaneous	uncertain or miscellaneous	uncertain or miscellaneous	uncertain	normal or miscellaneous	uncertain or miscellaneous
1	continental ice sheet	compound basin	piedmont	even, regular	snow and/or drift snow	marked retreat
2	ice field	compound basin	expanded foot	hanging	avalanche ice and/ or snow	slight retreat
3	ice cap	simple basin	lobed	cascading	superimposed ice	stationary
4		cirque	calving in sea	ice-fall		slight advance
5	valley glacier	niche	calving in sea grounded	interrupted		marked advance
6	mountain glacier	outlet	calving in lake			possible surge
7	glacieret and snow field	ice apron	confluent			known surge
8	ice-shelf	group				
9	rock glacier	remnant				

Table 3. Explanation of the morphology code of the glaciers.

sent ice margin here is stable and not a product of a 20th century maximum re-advance.

In the areas of recent glacier recession, minor variations occur. For the Inland Ice margin outlets reaching to near sea level, e.g. 2HQ02031 and 2HQ02034, Figs 3 and 8, a clear recession seems mainly to have occurred in the first half of the 20th century, followed by a minor readvance in the second half of the century. This development is known from other outlets of the Inland Ice in North and North-East Greenland (cf. Fig. 8). The recessional period may be related to warm spells with break-up of the fjord ice (e.g. Higgins 1989), and a correlation between glacial retreat and decrease in precipitation between 1920 and the 1950s (Diamond 1956) is suggested by Davies & Krinsley (1962). A decrease in precipitation during the past century is also suggested by the Hans Tausen ice corings (Reeh 1995).

The outlets of local glaciers , mainly from ice caps and ice fields, show for some lower and near-fjord lobes a minor recession during this century, whereas the inland areas situated close to the glaciation limit are dominated by stationary outlets (cf. Fig. 3). The thinning was locally initiated before 1938, to be followed by a slow-down (2KK04021), stationary (2LB04032) or readvancing (2HX01005) periods.

A downwasting of minor glaciers such as cirque glaciers, and presumably also some larger features such as ice caps, must be considered to have occurred throughout the 20th century. However, the net retreat and possibly also the thinning of the glaciers, is by the smallest amount so far encountered in Greenland.

Concluding Remarks

The assessment of Davies & Krinsley (1962) that most glacier margins in central Peary Land are extremely stable, also holds true for the situation in 1978. The apparant stability of glaciers approaches the conditions of Antarctic glaciers in the "Dry valleys" of Victoria Land (Chinn 1988), where it is precipitation changes rather than temperature

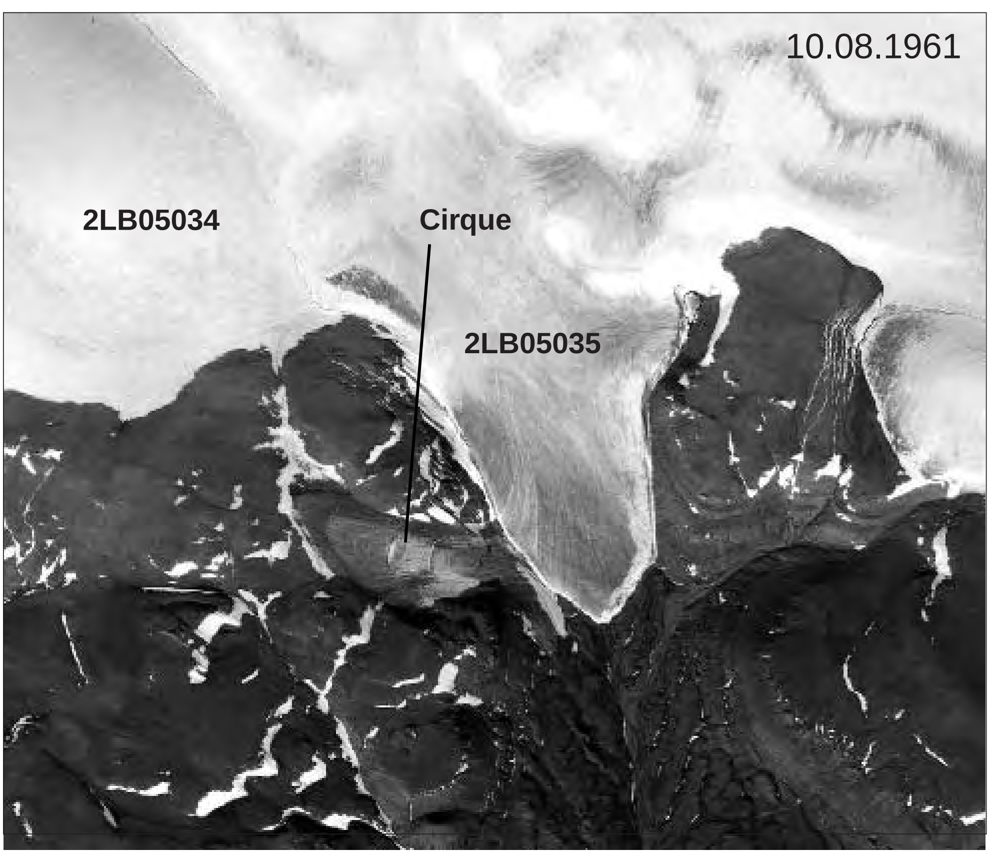


Fig. 10.
Top: South side of Hans Tausen Iskappe with the outlet of 2LB05035 and the adjoining cirque. On the far side of the lake Aftenstjernesø, the floating outlet of 2LB05030 (Astrup Bræ) can be seen. Photograph, KMS route 547M-V, no. 10403 of July 15th 1950.
Bottom: Outlet 2LB05035 and the adjoining cirque on August 10th 1961. Photograph, KMS route 256K no. 827. Both photographs copyright: Kort- og Matrikelstyrelsen.

changes that control the glacier changes; mean annual temperatures here are under –20°C.

The apparent stability of many central Peary Land glaciers may therefore be related to the thermal englacial and subglacial conditions such as freezing to the subsurface, low movement, i.e. low turn-over rate of the glacier mass. A partial control of glacier fluctuations by precipitation should also be considered, which again leads back to the question of the relationship of precipitation to fjord conditions, periodically ice-free and penodically semi-permanently ice covered during the arctic summer. The question is as to whether the ice-free fjords imply increased precipitation and accumulation on glaciers which might rule out the impact of higher temperature and ablation.

The record of net thinning of present ice caps and cirques points to a marginal, vertical downwasting rather than a horizontal recession (e.g. Reeh *et al.* 2001). Downwasting was also an important process during the Holocene deglaciation of North Greenland, as witnessed by extensive occurrences of dead ice terrain according to the descriptions of Kelly & Bennike (1992).

The largest fluctuations in Peary Land, as elsewhere in Greenland, are exhibited by the large calving outlets from the Inland Ice to the heads of the fjords (cf. Figs 5, 8). The high arctic NFG-mode (saw-tooth formed protruding fronts) is today a pronounced feature for most North Greenland Inland Ice outlets, and must be taken as a criterion for a semi-permanent ice cover of the interior fjord systems during most of the 20th century. Exceptions to this are the "normal" calving fronts (DJG-mode) from the large ice cap outlets into Frederick E. Hyde Fjord and the Inland Ice outlets (Academy Gletscher and Marie Sophie Gletscher) at the head of Independence Fjord. Since the NFG-mode again appears further south in East Greenland (in Hagen Fjord and Nioghalvfjerdsfjorden), these exceptions may be connected to oceanic circulation in these fjords related to the polynya off Northeast Greenland (e.g. Hjort 1997).

That oceanic circulation also played an important role for the onset and spread of the Holocene deglaciation in North and North-East Greenland can also be seen from the rate of recession of the Inland Ice outlets through the fjords. Attainment to the present positions was reached as early as 8-9 cal. ka B.P. in the larger fjords (local example: Independence Fjord, e.g. Bennike 1987) whereas it was reached later in narrow fjords as in the case of J.P. Koch Fjord near Hans Tausen Iskappe, where it was reached at about 6 cal. ka B.P.; this is also approximately the time of the isolation of this ice cap from the Inland Ice proper by the deglaciation of the valley Wandel Dal and the lake Aftenstjernesø (Fig. 10). The recession of Adams Gletscher in J.P. Koch Fjord continued beyond the present extent, and this retracted situation may have continued until the Little Ice Age (cf. Landvik *et al.* 2001), after which the glacier readvanced to its maximum at about A.D. 1900. Fluctuations in the 20th century are given in Fig 8.

The climatic deterioration occurred in a step-like fashion (Funder & Abrahamsen 1988; Bay & Fredskild 1997; Hjort 1997) and the occurrence of driftwood from 6.6 to 2.6 cal. ka B.P. (Landvik *et al.* 2001) indicates that the climate was periodically warmer than now more than 2600 years ago. The question as to whether ice-free fjords could contribute to increased snow accumulation in the surrounding highlands is still open.

The fluctuations of the local glaciers and of the Inland Ice can only in a very generalised way reflect the climatic development. The major recession from a neoglacial maximum in the first part of the 20th century and the quasi-stability or minor fluctuations in the last half of the century reflect the major temperature developments in the region, as also preserved in the Hans Tausen ice core record. A closer evaluation of this temperature record may contribute to an evaluation of periods of ice-free fjords as given by Reeh *et al.* (1999).

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