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SIR,

Extraordinary melt-water run-off near Søndre Strømfjord, West Greenland

During late January 1990, two melt-water rivers started to flow from the western margin of the Greenland ice sheet into Søndre Strømfjord despite air temperatures of below −30°C. Description of this unusual event is based upon local observations made by S. Malmquist (personal communication, May 1990).

The Ørkendalen river started flowing in the last week of January at one-third of its normal summer level (Fig. 1). One week later, melt water started to flow from Sandflugtsdalen river at approximately one-quarter of its normal summer level (Fig. 1). Both rivers continued to flow for a further 3 weeks during which air temperatures were consistently below −30°C. Discharge from these rivers over-ran the ice-covered fjord for a distance of 10 km (Fig. 1). A heavy freezing fog resulted from the exposure of relatively warm river water to sub-zero air temperatures. The fog was observed leading from the ice margin along the river channels towards the fjord by overflying trans-Atlantic aircraft.

From the above information, it was possible to quantify the volume of water involved in this event. Based on estimated "normal" summer discharges totalling $140\,\mathrm{m^3\,s^{-1}}$ for Ørkendalen and Sandflugtsdalen rivers, an estimated $90 \times 10^6\,\mathrm{m^3}$ of water were involved in this event. This figure probably underestimates the total volume of water drained but provides an approximation on which discussion can be based.

Until now, river flows have only been documented within the normal summer melt season (*c.* mid-May–*c.* mid-October). Not only are the flows described above outwith the usual period but they are in excess of those witnessed by the author in late October 1986 and early June 1987. As such, this event probably represents the release of stored melt water, as it cannot represent ice-surface ablation given the sub-zero temperatures.

Possible sources of stored melt water along this section of the ice-sheet margin include ice-dammed lakes and englacial or subglacial reservoirs. Ice-dammed lake drainage, although common within this region (Sugden and others, 1985; Russell, 1989; Russell and others, 1990), is unlikely to have resulted in this unseasonal outburst as there does not appear to be a suitably large lake located between Ørkendalen and Sandflugtsdalen melt-water streams (Fig. 1). The total volume of water drained during this event is 2.5 times that drained from an ice-dammed lake (Russell, 1989) and 300 times that noted by Russell and others (1990) for a small ice-dammed lake. Although this ice margin is likely to have been frozen to the bed during the winter months, sub- and/or englacial melt water originating at great distances from the ice margin may have still been travelling towards the ice margin down an equipotential gradient (Shreve, 1972). On meeting the cold, impermeable ice margin, melt water may have been stored as a sub- or englacial reservoir under considerable pressure. The release of water within such a reservoir is likely to have been maintained by high water pressures. The drainage of such a sub- or englacial reservoir located at a considerable distance from the ice margin may provide an explanation for the unusual events noted in Søndre Strømfjord in January and February 1990.

Although similar events may occur, unnoticed, during the summer melt flows, these winter discharge events may have important geomorphological effects upon the glacier margin and the pro-glacial river channels. The volume of water released in this event was far greater than that so far noted for any of the ice-dammed lakes within this area, constituting a significant part of run-off from this section of the ice margin.

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SIR,

Comments on: "6000-year climate records in an ice core from the Høghetta ice dome in northern Spitsbergen"

Fujii and others (1990) have recently presented an estimate of climatic conditions in northern Svalbard during the last 6000 years, based on their interpretation of an 85.6 m long ice

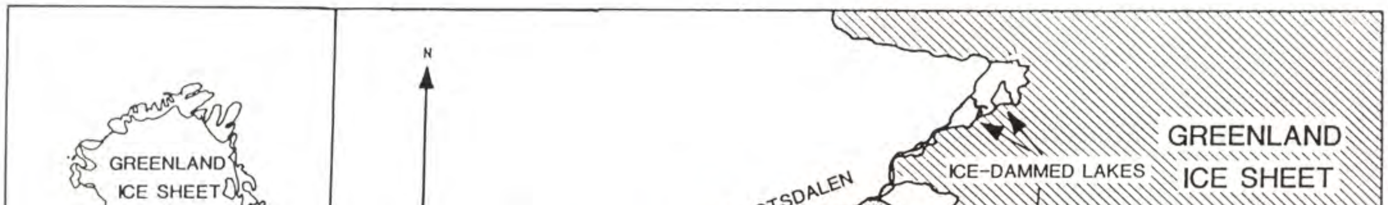

Fig. 1. Location map showing the melt-water routeways into Søndre Strømfjord, West Greenland.

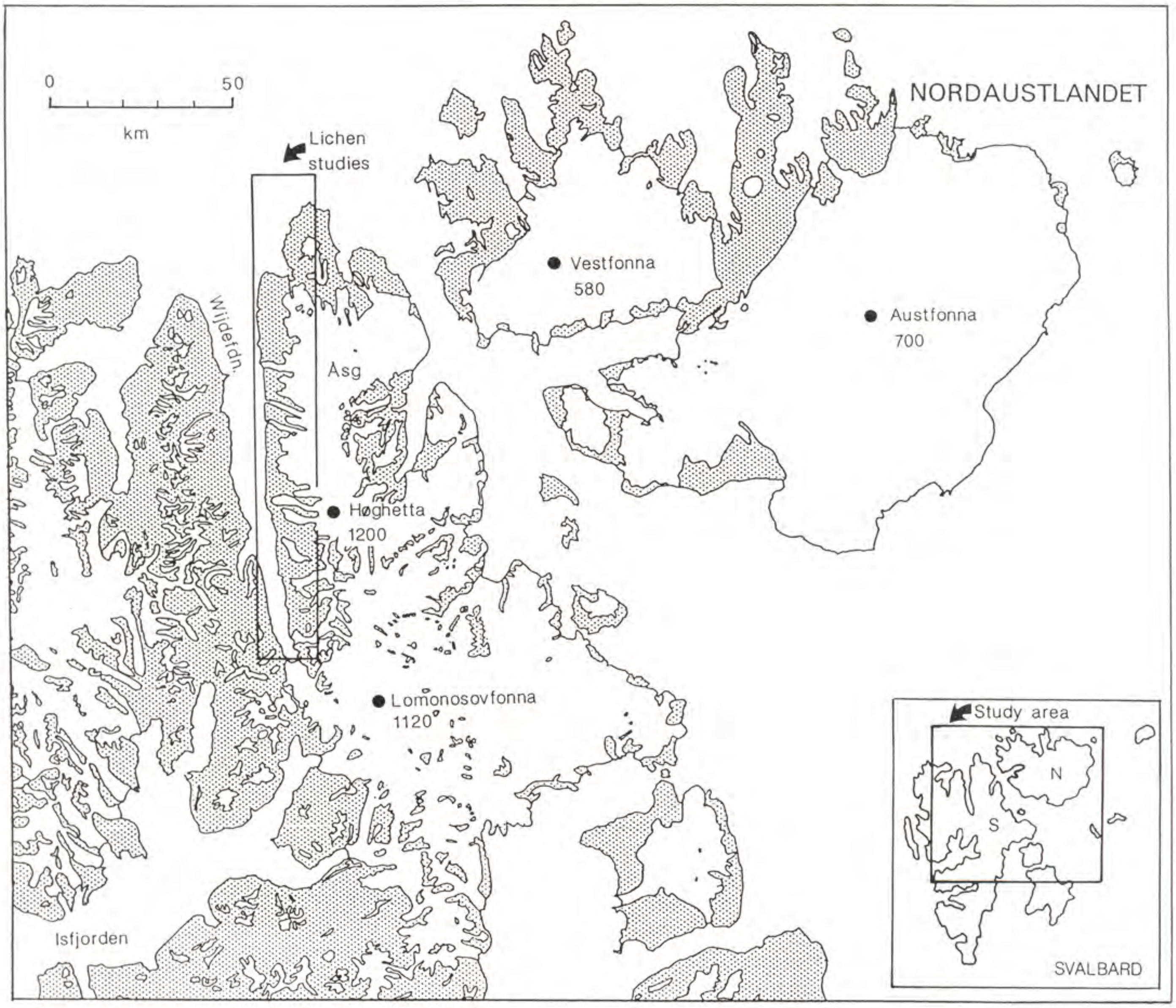

Fig.1. Location of ice-core sites (black dots) in northern Spitsbergen and Nordaustlandet, Svalbard. The name of each core site and its elevation above sea-level is given. The area of lichen studies on the east side of Wijdefjorden by Werner (1990, unpublished) is shown. Åsg is Åsgårdfonna. The inset locates the larger map within Svalbard. S is Spitsbergen and N is Nordaustlandet.

core. The core was collected in the spring of 1987 at an elevation of 1200 m on Høghetta (lat. 79°17′N., long. 16°50′E.), an ice dome on Åsgårdfonna in north-eastern Spitsbergen (Fig. 1). Several ice cores have been obtained previously in Svalbard, from ice masses on Spitsbergen and Nordaustlandet (Fig. 1). The difficulties of establishing reliable chronologies and environmental interpretations for these cores, which are subject to surface melting, water percolation, and refreezing effects in the relatively mild climate of Svalbard (Steffensen, 1982), have been discussed by several authors (e.g. Vaykmyae and others, 1977; Simões, unpublished). We should like to comment on the chronology and palaeoclimatic interpretation proposed by Fujii and others (1990) for the Høghetta ice core in the light of these interpretational problems, to point out that their conclusions are at variance with other proxy environmental data from Svalbard and the northern North Atlantic region, and to suggest a possible alternative chronology and climatic history for the core.

The chronology of the Høghetta ice core given by Fujii and others (1990) was based mainly on evidence from two methods: tritium content and radiocarbon (^{14}C) analysis. Taking tritium content first, a peak value at 1.6 m was interpreted by Fujii and others to represent the 1963 level. They stated that the uppermost 0.54 m of the core represented snow accumulated during the winter of 1986–87, and that superimposed ice was found immediately below this. This gave an accumulation rate of 4.7 cm a^{-1} between 1963 and 1986. They noted more minor tritium peaks at 1.95 and 2.3 m down-core, and assigned a date of 1959 to the latter level, yielding a mean annual accumulation rate of "about 20 cm of ice" for the 1959–63 period. An accumulation rate of 20 cm a^{-1} was then used to estimate ice-core age prior to 1963. The significantly lower accumulation rate for the period since 1963 was suggested to be a result of negative mass balance during some of these years.

Chronological control in the lowest 10 m of the core was derived by accelerator mass-spectrometer ^{14}C dates (from Nagoya University) on two bacterial colonies within the ice (at 75.3 and 85.2 m) and a frozen petal at 78.8 m. The bacteria colonies were suggested to have grown in melt-water pools on the glacier surface. The dates obtained were 5670 ± 100 year BP at 75.3 m, 4150 ± 290 year BP at 78.8 m, and 5480 ± 400 year BP at 85.2 m. Fujii and others pointed out that age inversion was present in this depositional sequence, but stated that the reason for this was not clear.

Fujii and others (1990) interpreted the palaeoclimatic record of the core as follows: (i) 85–50 m core depth: 6000–4000 year BP, very warm, palaeo-ice thickness about 35 m. (ii) 50–20 m core depth: AD 1770–1880, cold and stormy, Little Ice Age. (iii) 20–5 m core depth: AD 1880–1945, fluctuating warm-cold conditions. (iv) 5–0 m core depth: 1945–87, warm and more stormy. They inferred from this that there was a time gap in the core from about 4000 year BP to AD 1770. They ascribed this to negative mass balance over the period. The choice of 50 m depth for the location of the time gap was presumably related to changes in the values of reported parameters measured on the core (pH, electrical conductivity, sand particle and visible organic matter occurrence, air-bubble shape, and ice-type data). Fujii and others stated that the variability of pH values decreased below about 50 m, "suggesting a time gap at this depth". However, they noted an absence of sand particles between 20 and 60 m depth, and much bubble-free clear ice below 60 m. The requirement for a time gap is, therefore, a product mainly of the three accelerator ^{14}C dates towards the base of the core.

We suggest that the notion put forward by Fujii and others of a very substantial time gap in the ice-core record from Høghetta (and the palaeoclimatic implications that go with it) has not been fully justified by the available evidence, and that there are several arguments for a more straightforward interpretation of the core. We can see little evidence of major shifts in measured parameter values at 50 m depth which would *require* a hiatus of several thousand years in the depositional record to be invoked.

First, we believe that the interpretation of the Høghetta ice core should be undertaken with reference to the environmental context provided by existing palaeo-environmental data from Svalbard and the North Atlantic region. The inception of the Little Ice Age at AD 1770 proposed by Fujii and others (made necessary by a combination of the accumulation rate they adopted and their need for a hiatus within the core) is at variance with existing glaciological and climatic evidence from both geological sources and other ice-core records.

Lichenometric chronological evidence from 49 moraines on the east side of Wijdefjorden (Fig. 1), including those of several outlet glaciers of Åsgårdfonna (Fig. 1), and 92 moraines in western Spitsbergen, suggests that these ice masses reached beyond their present termini on four occasions during the last 1500 years (Werner, unpublished). In particular, Werner demonstrated the presence of two sets of Little Ice Age moraines for both Wijdefjorden and the west coast, indicating ice retreat from maximum positions at about 100 and 650 years ago. The clustering of lichen sizes into two groups suggests that the problem of possible inclusion of surge-type glaciers within the study has been minimized. Indeed, only one small outlet glacier of Åsgårdfonna (Longstaffbreen) has been observed to surge (Liestøl, in press). Werner pointed out that his lichen-growth curve was derived from the north-west coast (Werner, 1990), but in the colder, drier interior of Spitsbergen ages are likely to be older rather than younger than those predicted from the growth curve. This evidence for glacier advance is incompatible with a long hiatus to AD 1770 in the Høghetta ice core. Fossil tundra lying immediately below till in southern Spitsbergen has also been dated by ^{14}C methods to 760 ± 145 year BP, providing a maximum age for Little Ice Age inception in that area (Baranowski and Karlén, 1976). A Little Ice Age beginning in Svalbard significantly earlier than the late eighteenth century is also compatible with palaeoclimatic evidence from other areas bordering the northern North Atlantic, for example, Greenland (e.g. Crête core about AD 1300; Dansgaard and others, 1975), Iceland (AD 1300–1400; Lamb, 1982), and northern Fennoscandia (AD 1570; Briffa and others, 1990).

Ice cores have been obtained from a number of other sites in Svalbard by Soviet scientists (Gordiyenko and others, 1981; Punning and others, 1986; Arkhipov and others, 1987; Simões, unpublished). Their locations straddle the site at Høghetta geographically, with cores from Vestfonna and Austfonna to the east and Lomonosovfonna to the south (Fig. 1). The Lomonosovfonna core (50 km away) is most comparable to Høghetta in terms of its elevation (1120 m compared with 1200 m) and estimated equilibrium-line altitude (500–600 m compared with 800 m; Liestøl and Roland, *in* Steffensen, 1982). None of these other ice-core records, based upon oxygen-isotope stratigraphy and other physical and chemical parameters, has been interpreted to contain a time gap of any significance. Neither has the *inception* of the Little Ice Age been placed as late as AD 1770; a date of early fifteenth century has been derived by Simões (unpublished) for the Lomonosovfonna and Vestfonna cores.

Secondly, simple glaciological considerations make the existence of a time gap on the order of 4000 years within this 85 m long core, generated by a long period of "negative mass balance", unlikely. A very fine balance between mass inputs and outputs would have to be maintained over a very long period (approximately 4000 years) to preserve a 35 m depth of presumably stagnant ice. The moraine chronological evidence discussed above (Werner, unpublished) is particularly important, because some of the dated features are associated with outlet glaciers which are fed from Åsgårdfonna. Three sets of moraines beyond the present glacier margins, formed before AD 1770 but within approximately the last 1500 years, imply strongly that glacier net mass balance was positive over significant parts of this period.

We suggest that the evidence presented for the Høghetta ice core by Fujii and others (1990) could be interpreted in a rather different way. First, the accumulation rates they have used require revision. These were derived from the identification of two tritium peaks which are ascribed to 1963 and 1959. There are a number of problems in using this technique for dating cores from areas subject to strong summer melting, percolation, and flush-out. The peak at between 1.4 and 1.75 m is relatively small for the 1963 weapons testing explosions. The value recorded in the atmosphere in 1963 in the Svalbard region was about 5000 TU (tritium units) (International Atomic Energy Agency, 1969–79). When decay-corrected to 1987, this should be represented by a level of just under 1300 TU as compared with the 490 TU measured in the Høghetta ice core. This reduced peak, combined with the decrease in tritium below 1.75 m, suggests intense wash-out and probably percolation to lower layers (cf. Oerter and Rauert, 1982). The latter process would increase the tritium content of the lower layers above the natural background level of ≳25 TU. Furthermore, exchange between the melt water and snow/firn would have increased the original tritium level of these lower layers. We conclude, therefore, that the peaks below the highest concentrations could represent any year before 1963, and that 1.4 m depth is a maximum for the 1963 horizon. In our opinion, no credence can be given to the interpretation of the peak at 2.3 m as 1959 or any reliance placed upon the derived accumulation rate of 20 cm a^{-1}. This view is reinforced by scrutiny of climatic parameters measured at Svalbard meteorological stations. These are not compatible with the marked change (i.e. a 400% fall in accumulation rate) between 1959–63 and 1963–86 (Simões, unpublished). The 1960s in general was the coldest decade since 1920 and had some of the lowest number of melting degree days per year. Precipitation, in fact, had a quite clear trend to greater values during the 1960s and reached a maximum in 1972.

Secondly, the correlation of peaks in electrical conductivity and pH with volcanic horizons is notoriously difficult in the absence of other and independent chronological information. Given that the accumulation rate derived from the upper part of the core could be most uncertain, it is difficult to place any reliability in the depths, ages, and volcanic events given in table I of Fujii and others (1990).

Thirdly, we do not accept the requirement for a long time gap within the core on the basis of evidence presented by Fujii and others (1990), and would suggest that much of the core has accumulated more or less continuously within approximately the last 1000–2000 years. This interpretation de-emphasizes the importance of the ^{14}C dates, in part because they are inverted. We are not convinced that the evidence presented from the Høghetta core by Fujii and others justifies the 6000 years of climate records that they have described.

Finally, we hope that the further investigations of the Høghetta ice core mentioned by Fujii and others (1990), especially the oxygen-isotope profiles, will be published to shed additional light on its chronology and environmental record. We appreciate that the analysis of ice cores from areas of significant surface melting is particularly problematic, and hope that the Japanese Arctic Glaciology Expeditions (Watanabe and Fujii, 1988) will continue in their efforts to unravel the climatic signal in Arctic ice cores.

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