Climatic warming: a trigger for glacial iceberg surges ('Heinrich events') in the North Atlantic?

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In the present-day western North Atlantic, icebergs can be observed off north-east Canada, drifting south along the coast in the cold Labrador Current. Normally they melt in the area off Newfoundland where they reach warmer waters. Most of these icebergs originate from calving glaciers in West Greenland or in the Canadian Arctic. Jakobshavn Isbræ in West Greenland (Fig. 1) deserves particular mention as it is the fastest known ice stream in the world draining 6–7% of the entire Greenland ice sheet (Joughin *et al.* 2004). Southward drifting icebergs also occur along the east coast of Greenland (Fig. 2), but most of these melt when they approach the southernmost tip of Greenland. The iceberg limit in the north-western Atlantic varies from year to year, but isolated icebergs may reach far south of Newfoundland (Fig. 1). Many icebergs carry a load of rock debris and soil incorporated by their parent glacier that leads to deposition of ice rafted debris on the deep ocean sea floor.

In the past decade the Geological Survey of Denmark and Greenland (GEUS) has initiated marine geological investigations in the North Atlantic on the late Quaternary variability of North Atlantic thermohaline circulation, with special focus on the possible link between climate change and variations in deep-water flow intensity (Kuijpers *et al.* 1998, 2002, 2003). Moreover, glaciological projects in Greenland undertaken by GEUS have significantly contributed to the current debate of present-day climatic warming. Notably work carried out in East Greenland fjords has provided crucial information relevant for the study of glacial iceberg surges in the North Atlantic (Reeh *et al.* 1999). These surges are suggested to have been triggered under the influence of extreme cold climate conditions, but the actual trigger mechanism involved has been a matter of much debate.

Evidence from modern glacier process studies referred to above, combined with results of recent studies in the North Atlantic carried out by GEUS and partner institutions, has provided new insights into the possible trigger mechanism of these massive glacial iceberg surges. These new findings have great significance for the current climate debate, since they strongly suggest that ongoing ocean warming can trigger a sudden, massive break-up of ice shelves. Such processes may already be in progress in the Arctic (e.g. Vincent *et al.* 2004), where rapid ice-shelf disruption on the margin of the Ca-

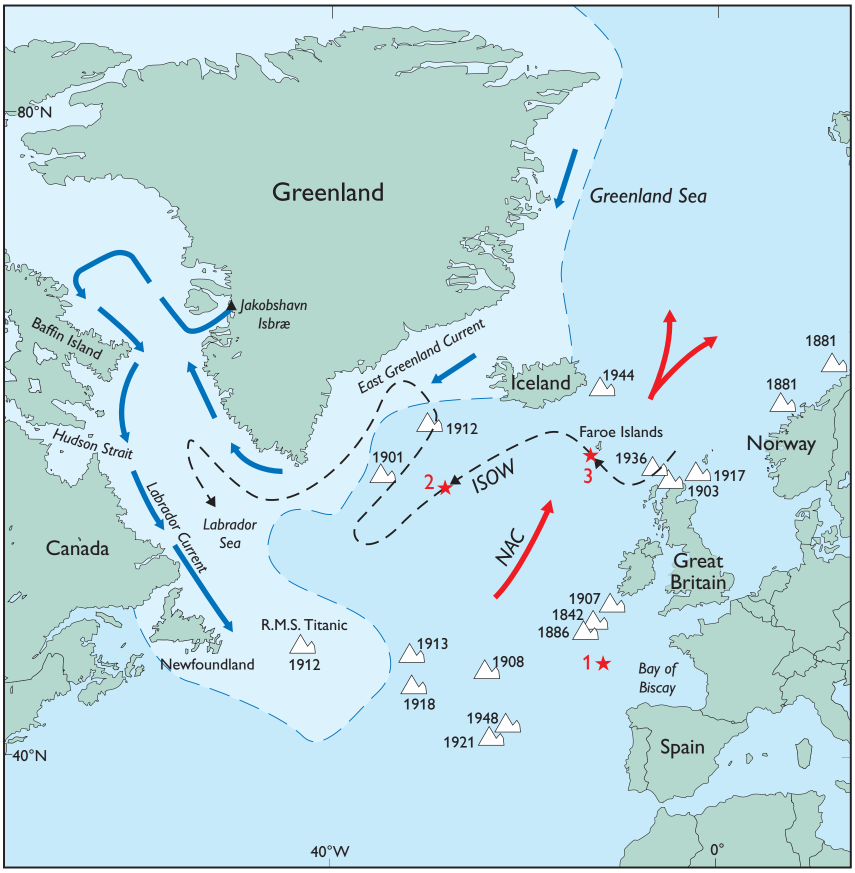

Fig. 1. Overview of the North Atlantic with iceberg drift pattern and exceptional iceberg observations. The main deep-water flow path of Iceland–Scotland Overflow Water (**ISOW**) and the study areas (**1**–**3**) mentioned in the text are also indicated. Locality 1 refers to the area north-west of Spain studied by Heinrich (1988), whereas **2** and **3** indicate study areas located along the ISOW deep-water flow path south of Iceland. NAC (**arrow**) shows northward transport of warm, saline water in the upper water masses by the North Atlantic Current. **Pale blue** indicates areas dominated by seasonal drift of icebergs.

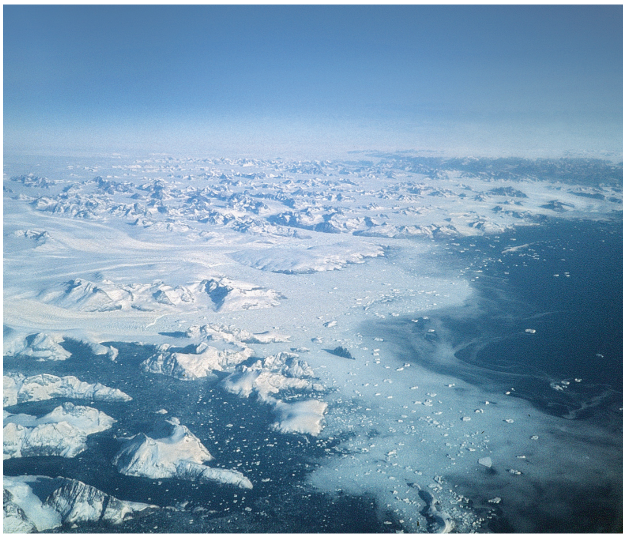

Fig. 2. The margin of the Inland Ice in South-East Greenland with outlet glaciers and numerous icebergs. Widespread slush (white) is observed in areas close to the coast.

nadian Arctic Ocean has been reported to be the result of significant warming over the past few decades. During this period intensified inflow of Atlantic water to the Eurasian sector of the Arctic has been noted. It is evident that for Antarctic ice shelves large-scale disruption and break-up may lead to significant destabilisation of the Antarctic ice sheet with the serious risk of a sudden, drastic sea-level rise.

Ice rafted debris layers and 'Heinrich events'

In the beginning of the 1980s several West European governments spent considerable funds on marine (geo)science investigating the possible option of future sub-seabed disposal of high-level radioactive waste, and the environmental risks of dumping low radioactive waste on the North-East Atlantic seabed. The German government supported marine geological investigations in an area of the eastern North Atlantic which had similar characteristics to the official Nuclear Energy Agency dump sites in the Bay of Biscay (Fig. 1). Up to 22 m long sediment cores were retrieved from water depths ranging from 3500 to 4500 m, and in the upper part of the cored sediment sequence a series of distinct layers rich in ice rafted debris (IRD) were identified (Fig. 3). The IRD layers mainly consist of sand and were formed during the last glacial cycle (Weichselian), which started around 110 000 years ago. These layers were further characterised by containing only very few tests of polar planktonic microfauna (foraminifera), much less than in the surrounding glacial sediments (Heinrich 1988). The estimated ages of the upper six IRD layers roughly correspond to times of major changes in the sea surface temperature of the northern Atlantic during the last glacial period. The lowermost IRD layer marks the initiation of full glacial conditions, and the uppermost layer the termination of the last ice age (Heinrich 1988). Soon after the publication of these findings similar layers were reported from sediment cores taken in the Labrador Sea (Bond *et al.* 1992; Broecker 1994). Subsequent investigations showed that the sand-size fractions of these layers were also characterised by elevated contents of detrital carbonate. Mineralogical investigations of the fine fraction of these deposits indicate that the IRD of some of these layers originated from the Greenland and North American region, while two of the layers included compounds of volcanic weathering products, possibly from the European Arctic (Jantschik & Huon 1992). Mineral ages (K-Ar) of the IRD were much higher than measured for surrounding glacial sediments. Another important observation was that the IRD layers thin by more than an order of magnitude from the Labrador Sea towards the eastern North Atlantic (Grousset *et al.* 1993), and that North Atlantic surface waters were extremely cold during their deposition. The latter conclusion was based on the high percentage of the polar planktonic foraminifera *Neogloboquadrina pachyderma* (sinistral), and is supported by low concentrations of ^{18}O in the foraminiferal calcium carbonate tests (Fig. 3). The drastic lowering of about 5°C of surface water temperature as well as the decrease of surface water salinity were thought to result from the melting of icebergs originating mainly from massive calving of the North American (Laurentide) ice sheet around Hudson Strait. Formation and south-eastward expansion of a cold meltwater lid may have led to the weakening or cessation of the North Atlantic thermohaline circulation system. Thus, transport of warm (saline) surface water via the North Atlantic Current (NAC) to northern high latitudes decreased, resulting in a dramatic cooling in Europe.

A detailed chronology established for these recurrent IRD events shows a spacing of about 11 000 years during the early glacial and about 7000 years during full glacial conditions. The significance of these massive iceberg discharge events for the understanding of the global climate evolution of the last glacial era led to the introduction of the term 'Heinrich events' (H-events) for these extreme glacial iceberg episodes in the North Atlantic (Broecker *et al.* 1992). In addition, possible links between H-events in the North Atlantic and the so-called Dansgaard-Oeschger (D-O) cycles recorded in the Greenland ice cores were investigated by Bond *et al.* (1993). The glacial Greenland ice core record (Dansgaard *et al.* 1993) shows marked millennial scale (1500 years) climatic cycles, revealing abrupt warming (5–10°C) within a few decades, subsequently followed by slow cooling and terminating in an extremely cold (stadial) period lasting tens to hundreds of

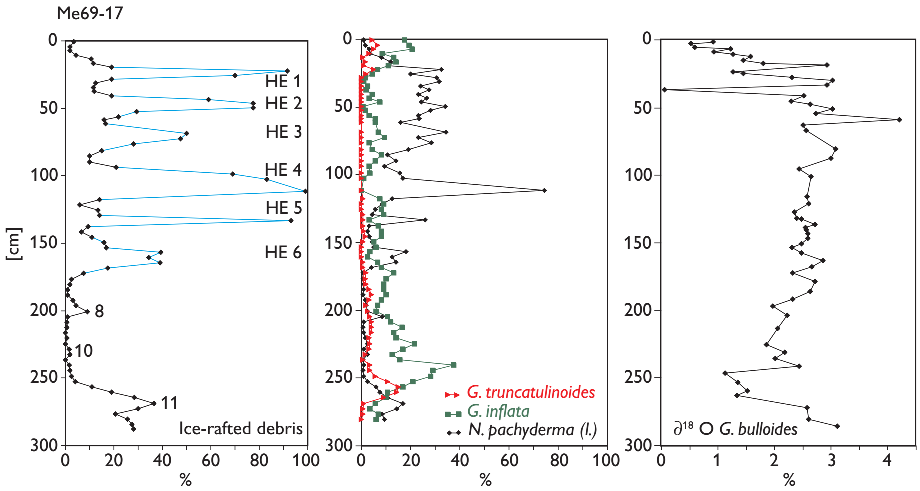

Fig. 3. Core record Me69-17 from the area north-west of Spain (locality 1 in Fig. 1). The amount of ice-rafted debris with peaks representing Heinrich events 1 to 6 (**HE 1–6**) is shown as part of the total split (IRD plus foraminifera), whereas foraminiferal species abundance is presented as part of the sum of the planktonic foraminiferal fauna. In addition, the stable oxygen isotope record of *G. bulloides* is shown. Slightly modified from Heinrich (1988), reproduced with permission from Elsevier.

years. Bond *et al.* (1993) demonstrated that H-events coincide with the coldest parts of a set of several D-O cycles and were immediately followed by significant warming. Meanwhile, large-scale glacial iceberg surges have been found not to be exclusively related to the North American region, but have also been documented for the North-West European ice sheet (e.g. Knutz *et al.* 2002).

Ocean subsurface warming and ice-shelf break-up

During the past decade numerous studies have been published dealing with possible trigger mechanisms for H-events. Possible explanations range from internal ice-sheet mechanisms (binge purge theory) to external forcing processes such as ice-load induced earthquakes, sea-level change, variations in solar forcing, enhanced tides and other mechanisms summarised by Alley & Clark (1999). Moros *et al.* (2002) proposed an alternative, new theory – outlined below – that relies on the observations of recent iceberg discharge processes and ice-rafting in East Greenland fjords reported by Reeh *et al.* (1999), who also described the implications of advection of Atlantic Intermediate Water at subsurface depth (> 200 m) for glacier and iceberg bottom melting and IRD distribution. Similarly, changes in glacial ocean subsurface circulation and associated heat transport play a key role in the theory proposed by Moros *et al.* (2002). As part of the global ocean thermohaline circulation system the North Atlantic Current (NAC) transports heat and salt via an upper flow (< *c.* 800 m) into northern high latitudes. After cooling in the Labrador Sea and Greenland Sea the density of the upper water masses increases, leading to convection and formation of cold, dense water flowing south as deep countercurrents. The occurrence of high salinities in the Greenland Sea is a crucial factor driving deep-water convection; low surface water salinity will lead to a weakening of the formation of deep, cold water. On their way south, the dense and cold water masses formed in the Greenland Sea can be traced in the northern North Atlantic as Iceland–Scotland Overflow Water (ISOW). By studying sediment records from cores taken along the ISOW flow path (Fig. 1, localities 2 and 3), Moros *et al.* (2002) demonstrated that ISOW flow intensified immediately before an H-event (Fig. 4).

In deep-sea sediments the silt fraction and other lithological parameters have proven to be a sensitive proxy for changing bottom water dynamics. Moros *et al.* (2002) found that increased flow activity, indicated by a coarsening of the silt fraction, precedes the maximum (continental) IRD input reflected by the quartz/plagioclase peak (Fig. 4). Thus, ISOW bottom current activity increased just before large-scale iceberg surging. Due to the coupling between the North Atlantic Current and ISOW, an increase in ISOW indicates that NAC also increased. Intensification of both deep ISOW and high NAC flow is a typical feature of climate warming (e.g. Kuijpers *et al.* 1998). During cold glacial climate times, the northward flow of warmer and more saline Atlantic water must initially have occurred below a cold surface layer, similar to that observed in the Arctic Ocean at present. This enhanced northward subsurface heat transport would increase bottom melting of floating outlet glaciers and ice shelves, ultimately resulting in ice-sheet destabilisation and massive iceberg surging. For icebergs to survive over large distances, as reported by the widespread IRD layers, initial ice melting must have been fast, creating an extensive cold, low-salinity surface layer. Thus, a marked cooling of the surface water was the consequence of initial, large-scale subsurface warming and melting. At lower latitudes in the North Atlantic simultaneous warming has been reported by various authors. This could explain the sudden rise in temperature a short time after the H-events, when the iceberg supply came to an end and the low salinity lid became fully mixed with the warmer water. The same mechanism of subsurface warming

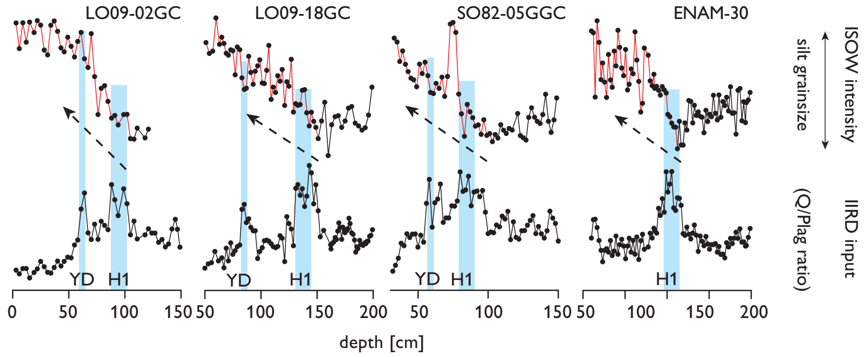

Fig. 4. Sections from three core records from the study area south of Iceland (**LO** and **SO** cores) and from south-west of the Faroe Islands (**ENAM** core; for location see Fig. 1). All show coarsening within the silt fraction indicating intensified flow of ISOW immediately before the H1 event. This occurred at the initial termination of the last deglaciation, slightly more than 15 000 years ago. The quartz / plagioclase (**Q/Plag**) peak indicates maximum IRD. Data from Moros *et al.* (2004).

as a trigger for outlet glacier melting and IRD production has recently been documented for the early Holocene retreat of Jakobshavn Isbræ (Lloyd *et al.* in press).

Future work

As outlined above, GEUS studies have hitherto been strongly focused on the northern North Atlantic. However, studies that deal with the reconstruction of oceanographic processes and iceberg drift in the Labrador Sea and Baffin Bay region have recently been initiated, and will include multi-proxy analyses of sediment cores.

Acknowledgements

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