FORCING OF DANSGAARD-OESCHGER CLIMATE CYCLES

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Summary

Two paleoceanographic multi-proxy records with multi-decadal resolution were obtained from the northwestern North Atlantic, to the south and north of the Denmark Strait. Phase relationships amongst the various signals of climate change in the 1/1460-y frequency band reveal that meltwater injections from East Greenland outlet glaciers (possibly enhanced by meltwater from Iceland) have probably formed the ultimate trigger in turning off the Atlantic thermohaline circulation, which has initiated abrupt and major stadial coolings. On the other hand, extensive iceberg melt and resulting sea ice cover over large parts of the mid-latitude North Atlantic has led to massive brinewater formation and finally, to a possible entrainment of warm surface water from the subtropics, thus to an abrupt reactivation of the Atlantic thermohaline circulation and the onset of interstadial conditions. Driven by enhanced interstadial snow accumulation rates and a strong sub-bottom relief, the East Greenland outlet glaciers quickly extended across the shelf, thereby inducing renewed surges and the next stadial.

Introduction

The recent discovery of a late Quaternary series of large-scale, quasi-periodical, decadal warmings and multidecadal coolings, the Dansgaard-Oeschger (D/O) cycles, has revolutionized thinking about global climate change. These millennial-scale cycles have been clearly documented in the polar ice records (Dansgaard and Oeschger 1989, Dansgaard et al. 1993; Grootes et al. 1993) and in various marine and terrestrial climate archives.

Some major characteristics of D-O cycles are largely established: (1) Abrupt polar temperature shifts from stadials to interstadials, which reach up to >10°C at the summit of Greenland and are paralleled by an abrupt increase in snow accumulation rate (Alley at al. 1993, Dansgaard et al. 1989); (2) a robust periodicity amounting to approximately 1460 years and the multiples of this interval (Grootes and Stuiver 1997); (3) the D-O cycles show maximum amplitudes during times, when the sea level dropped by more than 45 m, moreover, during times of glacial advance and retreat (Schulz et al. 1999); and (4) a clear anti-phase relationship between the temperature oscillations found in paleoclimatic records from the northern and southern Atlantic (Ninnemann et al., 1999), and from Greenland and parts of Antarctica (Blunier et al. 1998). This finding supports the concept of an oscillating "heat piracy" of the North Atlantic in the Central and South Atlantic (Berger and Wefer 1996), which results in a general warming of the South Atlantic during North Atlantic stadials, and viceversa.

Understanding the ultimate trigger and the causes of the various feedbacks and forcings involved with D-O cycles is an important key to a better comprehension and potential prediction of global climate change. In principle, the origin of D-O cycles may be linked to two different kinds of ultimate forcing mechanisms, (1) an El-Nino-style internal oscillator of the ocean thermohaline circulation (THC; Cane 1998) or (2) internal oscillations of polar ice sheets (MacAyeal 1993), the meltwater of which may induce cyclic fluctuations in the salinity of the North Atlantic surface water, in addition to (3) a number of secondary feedback mechanisms between the ocean, ice, and atmosphere. The model of an internal ice sheet oscillator which induces a North Atlantic salt oscillator (Broecker et al. 1990) is favored by many colleagues. However, Bond and Lotti (1995) and Bond et al. (1999) reported from North Atlantic sediment cores a major caveat to this model. They found that major drops in sea-surface temperature generally lead the deposition of ice-rafted debris (IRD) which records the surges of circum-Atlantic glaciers and thus should rather lead than lag the cooling events. Moreover, Bond et al. (1999) established a clear lead in the deposition of IRD characteristic of icebergs from East Greenland and Iceland to IRD which consists of detrital carbonate, originating from Labrador during the major stadials, the Heinrich events.

New Results from Irminger and Icelandic Sea Cores

Surface- and deep-water paleoceanographic records from sediments in the northwestern North Atlantic to the north (core PS2644) and south of the Denmark Strait (core SO82-5, Figure 1) exhibit particularly homogenous and large-scale fluctuations in surface- and deep-water circulation from 60 - 12 cal ka (Figure 2). The cores were dated by hundreds of C14 ages and via tuning the oscillations of a selected climate record in each sediment core to the temperature variations of the GISP2 ice record (Voelker et al. 1998). On the basis of foraminifera census counts and planktonic and benthic stable C and O isotopes with a time resolution of 50 and 80 years, the various oscillations reflect a master periodicity of approximately 1460-1500 y (Sarnthein et al. in press, van Kreveld et al. in press), such as the temperature cycles do in the ice records from Greenland.

Southwest of Iceland, *interstadial* summer sea-surface temperatures (SSTsu) average to >8°C and salinities (SSS) to 36 psu, thus recording a strong warm-water advection by the Irminger Current and accordingly, a strong Atlantic THC (Figure 2). In contrast, *stadial* SSTsu dropped abruptly down to 2-4°C, precisely in phase with SSS drops by 1-2 psu, but ahead of a subsequent stadial IRD spike (van Kreveld et al. in press). The stadial SSS reductions which appear more pronounced further upstream, in the southern Icelandic Sea (core PS2644), document great meltwater injections into the East Greenland Current near the onset of each stadial, when the Irminger Current was obviously turned off.

Frequent hematite grains in the IRD demonstrate that the initial meltwater probably originated from surging outlet glaciers in East Greenland. In addition, abundant basalt grains indicate an almost coeval iceberg injection from Iceland (Voelker 1999, Voelker et al. 1998). In the frequency band of the 1460-y cycle, the icebergs from East Greenland first arrived at the northern margin of Iceland, 80 y after the first meltwater signal, and were jammed for other 150-190 y north of the Denmark Strait, prior to reaching the Irminger Sea and central North Atlantic.

Each meltwater injection from East Greenland has led to a sudden and almost instantaneous turn off of North Atlantic Deep Water (NADW) formation in the major convection cells, located to the east of the East Greenland Current in the Greenland and Labrador Seas (Jung 1996; Elliot et al. 1998; van Kreveld et al. in press). As result, we find a coeval collapse in oceanic heat advection to the Greenland Norwegian Seas via the Irminger and Norwegian Currents, in harmony with various model simulations (Paillard and Labeyrie 1994, Rahmstorf 1995). The major surges from the Laurentian ice sheet, the Heinrich events which have occurred every 7200±2400 years, clearly lag those from East Greenland by several hundred years and have probably been induced by a slight sea-level rise subsequent to the glacial surges from East Greenland and Iceland.

The end of each stadial is marked by the striking D-O event of abrupt warming. On the basis of the two new sediment records, phase analysis in the 1/1460-y frequency band reveals a pecularity: Such as the onset of the stadials also the onset of the D-O interstadials was probably tied to iceberg melt. It triggered extensive seasonal sea-ice and abundant brinewater formation in the largely meltwater covered northwestern North Atlantic, similar to the modern regime near to Antarctica. This ample brinewater convection may finally have entrained, with a short phase lag of 130-155 y or less, warm surface water from the subtropics. We may consider this mechanism as *the* trigger for the sudden reactivation of Atlantic THC, which has involved the outstanding temperature rise on Greenland and a coeval global response of ocean and atmospheric circulation and continental climate, with ramifications up to the northwest Pacific (Kiefer et al. in prep.).

Subsequent to the D-O events the interstadials are characterized by an abrupt and significant increase in snow accumulation rates (Dansgaard et al. 1989). They necessarily lead to an increased growth of the Greenland ice sheet across the shelf and finally, after approximately 750 y, to the next surge of the major outlet glaciers in East Greenland and thus, to the next stadial. These outlet glaciers have reached a maximum ice thickness of 800-850 m on the shelf (Funder et al. 1998) and may just reveal the appropriate binge-purge interval because of the marked mountain relief in East Greenland, distinguishing this ice sheet from the large low-land ice sheet on Laurentia and the small-scale ice sheets on Iceland.

Major problems are still linked to the understanding of the Holocene climatic cycles, when the temperature amplitudes on Greenland have almost ceased and the Greenland glaciers, serving as potential trigger, may have retreated further back into the fjords. However, climatic cycles in the frequency range of D-O cycles have persisted through the Holocene in most parts of the world (e.g., Sirocko et al. 1996, Wang et al. 1999), including evidence of periodic surging from East Greenland glaciers (Bond et al. 1997) and coeval variations in overflow intensity (Bianchi and Mc Cave 1999)

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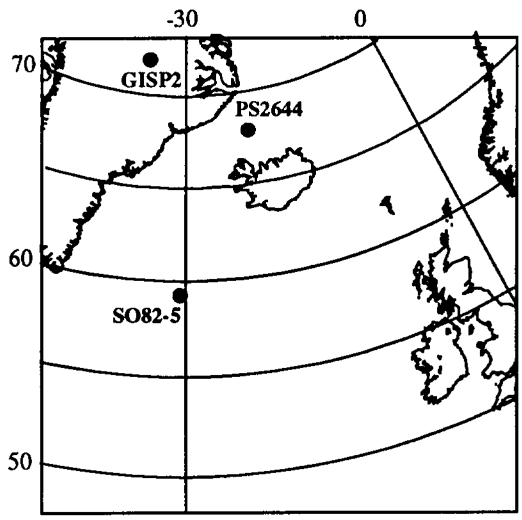

Figure 1: Location of sediment cores SO82-5 (59°N, 31°W, 1416 m water depth) and PS2644 (68°N, 22°W, 780 m water depth), and GISP2 ice core (73°N, 39°W).

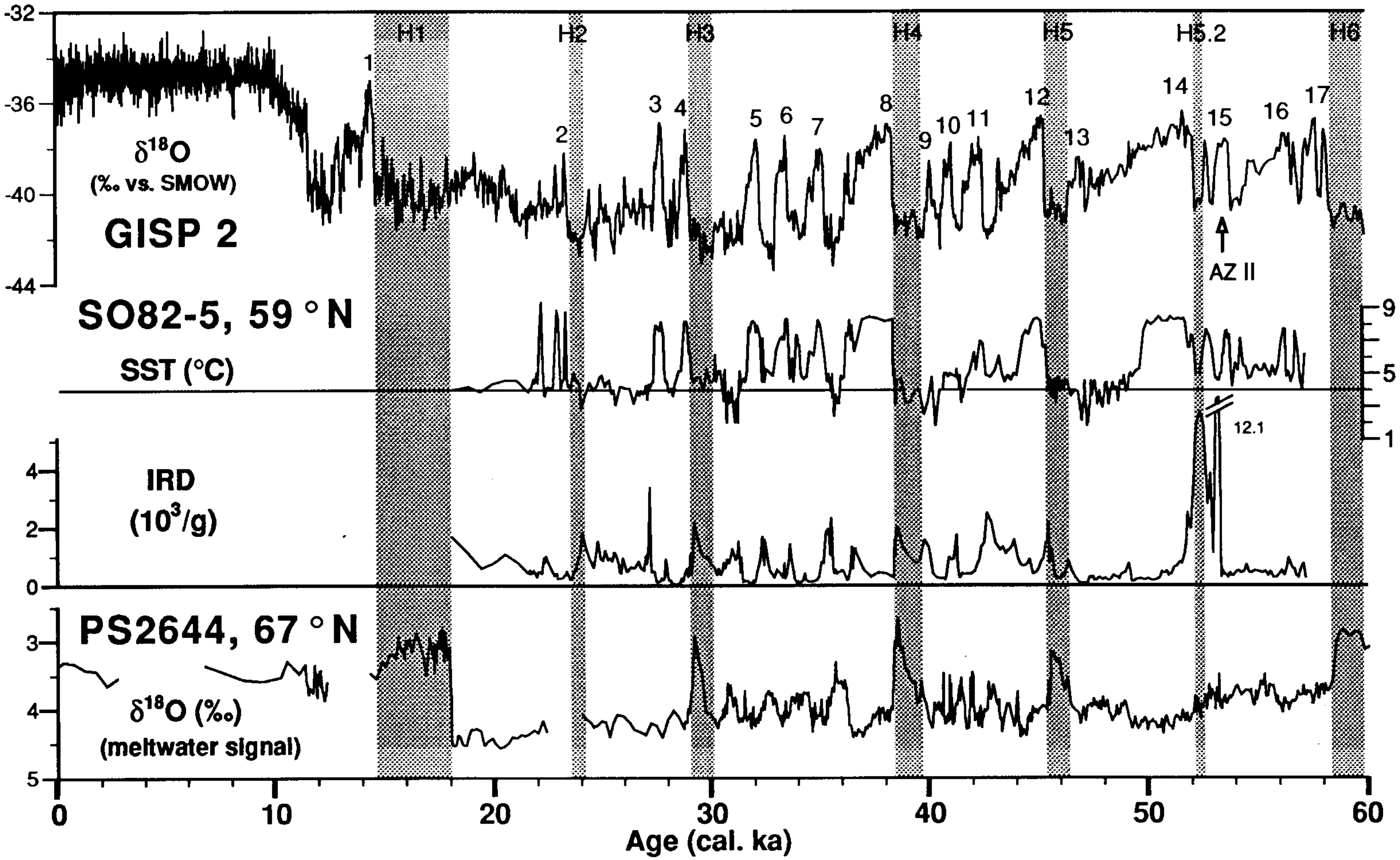

Figure 2: GISP2 $\delta^{18}O$ temperature record on Greenland summit of the last 60,000 calendar (cal) y (Grootes and Stuiver, 1997) compared to SST temperature and ice-rafted debris (IRD) curves of marine sediment core SO82-5 and planktonic $\delta^{18}O$ meltwater record of marine sediment core PS2644. Numbers on GISP2 record are Dansgaard-Oeschger interstadials, gray bars mark Heinrich events H1-H6. AZ II = North Atlantic Ash Zone II (van Kreveld et al., in press; Voelker, 1999).