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High-resolution climate records from the North Atlantic during the last interglacial

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THE two deep ice cores recovered by the GRIP[1] and GISP2[2] projects at Summit, Greenland, agree in detail over the past 100,000 years[3] and demonstrate dramatic climate variability in the North Atlantic region during the last glacial, before the current period of Holocene stability. This glacial climate instability has subsequently been documented in the marine sedimentary record of surface-ocean conditions in the North Atlantic[4]. Before 100 kyr ago the two ice core records are discrepant, however, casting doubt on whether the oxygen isotope fluctuations during the last interglacial (Eemian) seen in the GRIP core[1,5] represent a true climate signal. Here we present high-resolution records of foraminiferal assemblages and ice-rafted detritus from two North Atlantic cores for the interval 65 kyr to 135 kyr ago, extending the surface-ocean record back to the Eemian. The correlation between our records and the Greenland ice-core records is good throughout the period in which the two ice cores agree, suggesting a regionally coherent climate response. During the Eemian, our marine records show a more stable climate than that implied by the GRIP ice core, suggesting that localized phenomena may be responsible for the variability in the latter record during the Eemian.

We have examined two cores (DSDP site 609, V29-191) from the eastern North Atlantic (Fig. 1) at a depth spacing corresponding to approximately 200 years throughout marine isotope stage 5 (MIS 5). This stage was broadly defined as an interglacial period in the original oxygen isotope stratigraphy[6] and subsequently partitioned into substages 5a to 5e, with 5e alone correlative with the last interglacial (Eemian) in terrestrial records[7]. The two cores bear evidence of repeated encroachment of polar surface waters. While advances across a 20° swath of latitude have previously been documented on orbital timescales[8,9], water-mass migrations evident in this study are correlative with the higher frequency changes occurring on the Greenland ice sheet, beginning ~110,000 years ago[1,2]. Since at least this time, cooling on the ice cap and at the sea surface have been linked.

Two indicators of oceanographic conditions were utilized for this study: the planktonic foraminiferal assemblage and the abundance of ice-rafted detritus (IRD), measured relative to coarse biogenic particles and to total sediment. Time series of these proxies are remarkably similar (Fig. 2). This similarity of

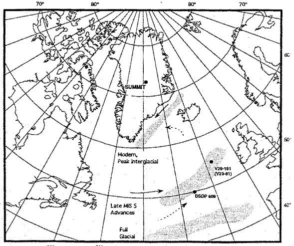

FIG. 1 Study area in North Atlantic. The Greenland location is the ice-core drilling site at the summit of the ice sheet. Ocean locations are sites of sediment cores used in this study. DSDP site 609 was drilled in a local basin on the eastern flank of the Mid-Atlantic Ridge. V29-191 was cored on an abyssal drift deposit along Feni ridge. V23-81 is a nearby core used for a previous comparison with the glacial portion of the Greenland record. Shaded areas represent the approximate location of polar water boundaries. Solid arrows indicate cold, fresh Arctic/sub-Arctic flows. Dashed arrows indicate warm, saline subtropical/subpolar flows.

sedimentary data from two widely spaced cores, representing the disparate depositional environments of local basin and abyssal drift, attests to the accurate recording of widespread oceanographic conditions.

Each of our records contains peaks of polar foraminifera (*N. pachyderma s.*) and IRD which rise above low ambient values. This background has a value of a few per cent for much of the study interval, and is at or near zero in sediment representing MIS 5e. Eight warm-cold oscillations are evident in the faunal record between the glacial inception at ~110 kyr (before the present) and the end of MIS 4. The ramping structure so prevalent in the subsequent glacial period[3] is absent here. IRD abundances increase and diminish repeatedly, culminating in Heinrich event H6 (ref. 10).

Relatively mild conditions prevailed in the subpolar surface North Atlantic for most of MIS 5, while polar conditions occurred as transients. This finding is consistent with the view that maximum warmth is limited to the peak interglacial MIS 5e while recurrent climate amelioration occurred throughout MIS 5 (ref. 11). Similar evidence of mild climate punctuated by cool intervals characterizes high-resolution terrestrial records which are interpreted as correlative with MIS 5 (refs 12, 13).

Episodic polar influence at these sites implies the repositioning of an oceanic front at the boundary between surface currents originating in the Arctic and subtropical Atlantic (Fig. 1). On a glacial/interglacial timescale, frontal migrations over a given site are captured in sediments as a nearly square-wave transition between extreme proxy values. The moderate abundances of polar fauna during cool events within MIS 5 indicate the proximity of our core locations to a dynamic polar front. As indicated by the peak values, V29-191 was near the mean position of the frontal zone during intermediate polar advances, while DSDP site 609 was nearer the southern edge of the zone.

The inferred location of the surface water-mass boundary has important implications for thermohaline circulation. Such a configuration implies restricted northward export of saline surface waters from the Atlantic in conjunction with reduced deep ventilation and production of North Atlantic Deep Water (NADW) in the Nordic Seas. Deep circulation is one mechanism capable of influencing Greenland air temperatures, by way of surface

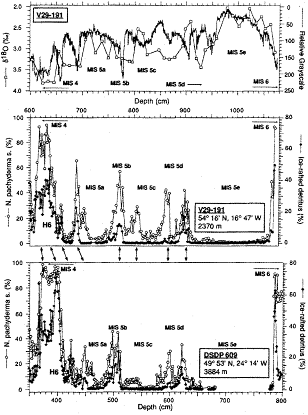

FIG. 2 Time series showing climate proxies from marine sediment cores plotted against depth. Oxygen isotopes were obtained from the benthic foraminifera *Cibicidoides*. Greyscale curve is derived from relative reflectivity measurements on digitized sediment images. *Neogloboquadrina pachyderma sinistral*, a planktonic foraminifera, is associated with polar surface waters. Variations in the abundance of this species, measured as a percentage of the total planktonic foraminifera, are indicative of the prevalence of polar conditions at a given site during the several centuries represented by a single sample. Arrows indicate eight peak polar abundances. Increases in polar formaminifera come largely at the expense of a subpolar assemblage dominated by *Neogloboquadrina pachyderma dextral* and *Globigerina bulloides*. Ice-rafted detritus abundance is calculated as the percentage of coarse terrigenous grains (>150 μm) to total coarse particles including biogenic remains. Such large particles are unlikely to be carried long distances by mechanisms other than floating ice[23,24].

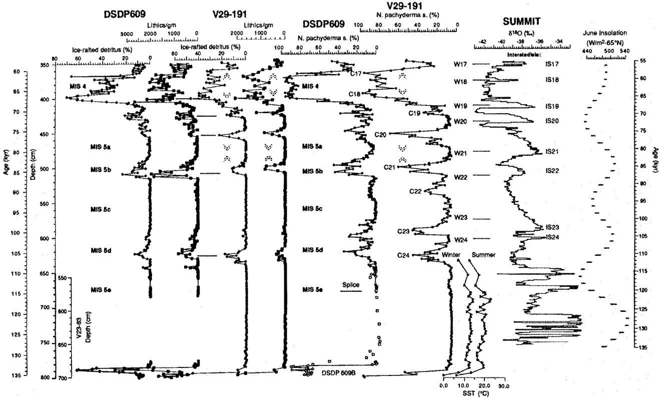

FIG. 3 Comparison of deep sea cores with GRIP ice core from Summit, Greenland. Isotopic composition of precipitation over Greenland, preserved as ice, reflects distillation of atmospheric water vapour during poleward transport. Ice core is plotted against age based on flow of thinning ice. DSDP site 609 is plotted against depth below the sea floor. Spliced data is from nearby core V23-83 (ref. 25). V29-191 record has been stretched in MIS 4 and compressed in MIS 5a to match DSDP site 609, accounting for differences in sedimentation rates. Numbered marine polar episodes, *C*; Numbered subsequent warmings, *W*. Lithic concentrations and IRD per cent represent the ratio of coarse (>150 μm) terrigenous fragments to bulk sediment weight and total coarse particles (terrigenous fragments + foraminifera tests) respectively.

ocean heat transport, on the observed millenial timescales, which are not easily explained by orbitally influenced insolation anomalies. Changes in the mode or flux of NADW would also provide global communication of regional conditions.

The relationship between IRD and the foraminiferal assemblage is interesting. Each increase in IRD is associated with an increase in polar foraminifera but not all the increases in polar foraminifera are accompanied by increased IRD. This distinction is important. Colder seas occurred in conjunction with the arrival of debris-laden icebergs, but colder seas alone were insufficient to enhance IRD. The IRD influxes are equal in number and similar in amplitude to increases in $\delta^{18}O$ apparent in high-resolution benthic records[14], and may be linked to early stages of ice growth on surrounding land masses. Greater amounts of IRD at DSDP site 609 than at V29-191 thus reflect iceberg surface trajectory, as proposed for younger IRD events[15], and enhanced deposition at the southern edge of an iceberg-laden current.

Enhanced IRD deposition began with the initial advance of polar waters relatively early in MIS 5. This may indicate rapid growth of Northern Hemisphere glaciers, accounting for much of the fall in sea level and increase in seawater-$\delta^{18}O$ associated with MIS 5d. Alternatively, nucleation of glaciers may have occurred near enough to the surrounding coasts to allow ice margins to reach the sea early during ice growth.

It is interesting to consider the IRD peaks in the context of the six Heinrich events of the last glacial period[15]. Our study reveals four more events within MIS 5 and another at termination 2, for a total of 11 during the last climate cycle. This is exactly the number postulated by Heinrich[16], but not identified in his study of low sedimentation-rate cores. The event associated with termination 2 shares a suite of characteristics with the younger glacial events[17] (for example, detrital carbonate, foraminifera minimum), while it remains to be seen if the MIS 5 events constitute interglacial equivalents of Heinrich events.

The eight intervals of enhanced polar influence are easily correlated with decreased temperature on Greenland, as deduced from ice sheet $\delta^{18}O$. Subsequent retreats of polar waters thus correspond to the oldest eight interstadials identified in Greenland ice (Interstadials 17–24)[1]. Each of the warm and cold events can be matched between records on a one-to-one basis (Fig. 3), as well as on the basis of pairs of cold events associated with MIS 4, 5b, 5d and the 4–5 boundary. This observation supports a climatic interpretation of this portion of the Greenland record and is further evidence of the deep sea's capacity to record high-frequency variability.

We used published age models for the GRIP ice core[1] and DSDP site 609 (ref. 4) to establish a chronology for comparison. Although temporal models based on the flow of thinning ice and constant sediment accumulation contain significant uncertainties, these independent timescales put our correlation to a simple test which goes beyond establishing that eight events occurred during a given interval. The largest difference between age estimates for correlative cold events occurs for the earliest two, and are of the order of 5,000 yr (Fig. 3). All of the others agree with an average of 1,200 yr, a reasonable figure given the estimated errors and uncertain phase relationships.

Differences in the amplitudes of excursions in the compared records are evident in two cycles on the MIS 4-5 transition. They are anomalously pronounced in the ice cores, to the extent that their isotopic composition implies conditions which were not only colder than the ensuring MIS 4 but more severe than virtually all of peak glacial MIS 2. Our records of the MIS 4-5 transition more closely resemble the distinct intermediate oscillations previously documented in sea surface[18] and deep ocean records[19]. These events are real, yet their ice core expression may incorporate differing water-vapour sources[20] and/or may reflect local or high latitude climate amplification, perhaps associated with the glacial transition.

Below substage 5d, the correspondence between our marine records and the ice core record breaks down. This observation bears reflection, considering the subsequent similarity. Because DSDP site 609 is not continuous through MIS 5e, V29-191 is better suited for comparison. The signature, if any, of unstable peak interglacial climate in this core is extremely muted, in contrast to the clear expression of younger events that are similar in amplitude and duration. One possibility for this lack is that our proxies are saturated throughout and that the Eemian climate was unstable while remaining warmer than all ensuing intervals of MIS 5. While this view is not completely supported by the GRIP record itself, which implies Eemian intervals substantially cooler than subsequent interstadials and nearly as cold as some subsequent stadials, it does appear that the abundance of polar fauna reaches a practical minimum in MIS 5e. Estimates of sea surface temperatures derived from the more diverse foraminiferal assemblage display a limited amount of variability about a longer term rise and fall through the peak interglaciation. A second possibility is that the subpolar North Atlantic was decoupled from atmospheric conditions over Greenland during MIS 5e[21]. In this case the GRIP record from Summit may contain the imprint of local climate variability. A third possibility is that the Eemian instability represents a different non-local phenomenon from the ensuing record, for example source region variability rather than temperature. It is also possible that the integrity of the ice core records has been compromised. Duplicate records remain the best test of this possibility, and they are most likely to come from the deep sea. Recent evidence from the Bahama Outer Ridge suggests a similar structure in benthic indicators[22]. No equivalent ice cores will be recovered for some time, and while careful scrutiny has failed to demonstrate anomalous deformation within the mid and late Eemian section of the GRIP summit core, the GISP2 ice core, drilled near the summit site, is clearly disturbed throughout the interval of interest[3] and cannot be used to support the GRIP record. Although this is not the last word on Eemian instability, the deep-sea record appears to hold the key in the near future. □

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