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Evidence for regional cooling, frontal advances, and East Greenland Ice Sheet changes during the demise of the last interglacial

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ABSTRACT

High-resolution lithic and sea surface climate records are used to portray the progression of North Atlantic climate, hydrography, and Greenland Ice Sheet (GIS) activity through the peak of Marine Isotope Stage (MIS) 5e into the last glacial inception. We use Eirik Drift sediment core MD03-2664 (57°26.34′N, 48°36.35′W), recovered south of Greenland, strategically located to monitor fluctuations in GIS extent and iceberg calving events. Our results show that a significant amount of ice-rafted debris (IRD) was present during the early MIS 5e, until gradually tapering off by 122 kyr BP due to a diminishing GIS. Sea surface temperatures (SSTs) in the northern subpolar gyre reached peak values early in MIS 5e coinciding with peak insolation. Regional cooling leading to the demise of the last interglacial started prior to the end of the MIS 5e benthic $\delta^{18}O$ plateau, at approximately 119 kyr BP, as summer insolation waned. This gradual cooling trend is interrupted by an abrupt and brief cooling episode at ~117 kyr BP. Increased IRD abundance during the 117 kyr BP cooling event suggests that regional ice sheet growth occurred prior to the end of the MIS 5e benthic $\delta^{18}O$ plateau, and the major glacial inception. SSTs south of Greenland followed a two-step cooling during the glacial inception similar to the pattern observed across much of the North Atlantic and Europe. Benthic $\delta^{18}O$ increases in parallel, suggesting that this two-step cooling is linked to a two-phased intensification of Northern Hemisphere glaciation.

1. Introduction

The last glacial inception is characterized by significant cooling of the high latitudes, and the advance of Northern Hemisphere ice sheets amplified by the declining Northern Hemisphere summer insolation. The evolution of climate and ice sheets through this important transition provides insight into climate and ice sheet sensitivity. Under what forcing conditions do ice sheets nucleate and which areas are most sensitive? There is indirect evidence from sea level records (e.g., Thompson et al., 2011) that ice sheets do vary during interglacials, and that these variations may become more significant/larger in amplitude as Northern Hemisphere summer insolation wanes. Yet the loci of ice sheet growth/variability remains poorly constrained due to the limited number and distribution of records constraining past ice sheet changes.

A frequently used proxy for ice sheet variability is ice-rafted debris (IRD), which comprises lithic grains transported by calving glaciers that drift and melt with prevailing ocean currents. Therefore, the presence of icebergs is the determining factor for IRD deposition at any given location, and the amount of IRD is attributed to the supply rate of calving glaciers (Jansen et al., 2000). Indirectly, the presence of IRD in pelagic sediments thus provides evidence for marine terminating glaciers at the time of deposition. Detailed studies of sediment cores from the Nordic Seas and subpolar North Atlantic, that span the last glacial cycle have documented that there is a high degree of correlation between the advance of ice sheets and the magnitude of IRD peaks in open ocean sediments (Baumann et al., 1995; Dokken and Jansen, 1999; Fronval et al., 1995; King et al., 1996; Mangerud et al., 1996; Sejrup et al.,

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2000). IRD records therefore provide a means to reconstruct ice sheet dynamics and their interaction with the climate system, providing evidence of both source and location of ice sheet melting (Bond and Lotti, 1995; Ruddiman, 1977).

North Atlantic IRD records spanning the last interglacial suggest the following sequence of events: a high and variable IRD deposition characterizing late Marine Isotope Stage (MIS) 6; a significant increase in IRD marking a massive iceberg discharge associated with Heinrich Event 11 (H11) at the end of MIS 6; a reduction to near-zero IRD abundance through MIS 5e; and generally low abundances until late MIS 5d, followed by a well-known sequence of IRD events through the rest of MIS 5 (i.e., cold episodes C24-19) (Bauch and Kandiano, 2007; Chapman and Shackleton, 1999; Hibbert et al., 2010; McManus et al., 1994; Oppo et al., 2001, 2006). Climatic instability in the North Atlantic during the youngest substages of MIS 5 (5a-5d) was documented by McManus et al. (1994), based on increases in both the IRD content and the abundance of the polar planktonic foraminifera *Neogloboquadrina pachyderma* (sinistral), which suggested advance of polar waters and rapid growth of Northern Hemisphere glaciers (e.g., McManus et al., 1994). Related abrupt cooling and IRD events were later documented for the MIS 5e/5d transition and also within MIS 5e (Chapman and Shackleton, 1999; Mokeddem et al., 2014; Oppo et al., 2001, 2006). However, variations in the spatial distribution and magnitude of these cooling and IRD episodes exist within the North Atlantic.

Evidence from the Nordic Seas and subpolar North Atlantic IRD records indicate that tidewater glaciers reached the margins of the Nordic Seas within MIS 5e, suggesting a relatively early initial growth of regional ice sheets (e.g., Fronval and Jansen, 1997; Oppo et al., 2006). These early increases in IRD during MIS 5e were interpreted as increased influence of polar waters, possibly influenced by solar forcing (Bond et al., 2001), whereas larger events following the glacial inception involved ice sheet instability (Chapman and Shackleton, 1999).

Here, we present new high-resolution multi-proxy records from the Eirik Drift—a high accumulation rate site off southern Greenland, which lies in an important and under-constrained region within the northern Subpolar Gyre (SPG). In particular, the location is ideal for identifying the initial southward incursions of polar water and ice rafted material due to its proximity to the modern polar and arctic fronts and to the southward transport trajectory of icebergs calved from Eastern Greenland's tidewater glaciers. Here we adopt the definition of Polar Front as the boundary between Polar and Arctic waters, and Arctic Front as the boundary between Arctic and Atlantic waters (Swift and Aagaard, 1981). High-resolution lithic and surface climate records from Eirik Drift, together with previously documented records from the Nordic Seas and subpolar North Atlantic, provide new constraints on the co-evolution of North Atlantic climate, hydrography and ice sheet changes in unprecedented detail during the demise of the last interglacial.

2. Core location and oceanographic setting

New high-resolution lithic and sea surface climate records are obtained from the Eirik sediment drift core MD03-2664 (57°26.34′N, 48°36.35′W, 3442 m water depth), which is situated 370 km southwest of Cape Farewell in the Labrador Basin (Fig. 1). This site is sensitively situated with respect to the Greenland Ice Sheet (GIS) and provides the temporal fidelity necessary to detect abrupt perturbations to regional hydrography and climate during the evolution and demise of the last interglacial period. In order to place these changes into a regional context, differentiate between local and regional influences, and map the spatial progression of frontal systems and SPG geometry, the new records are compared with published records from Ocean Drilling Program (ODP) Site 980 and core NEAP-18K from the northern North Atlantic Ocean and core HM57-7 from the Iceland Sea (Chapman and Shackleton, 1999; Fronval and Jansen, 1997; Oppo et al., 2006) (Fig. 1; Table 1).

The Eirik sediment drift accumulates rapidly as a result of the influx of sediments eroded from the Denmark Strait and eastern Greenland margin suspended in Denmark Strait Overflow Water (DSOW) (Wold, 1994). DSOW combines with North West Atlantic Deep Water (NWADW) to form the Western Boundary Undercurrent (WBUC) (McCartney, 1992). Core site MD03-2664 lies just below the main axis of the sediment-laden WBUC and hence preserves expanded interglacial sediment sequences (Hillaire-Marcel et al., 1994).

MD03-2664 is located at the northern edge of the SPG which dominates the surface water hydrography of the northern North Atlantic (Hátún et al., 2005) (Fig. 1). The North Atlantic Current (NAC) forms the eastern segment of the gyre, carrying warm and saline waters northward, while the southward flowing, cold and fresh East Greenland Current (EGC) dominates the western boundary. The EGC, together with the smaller East Greenland Coastal Current (EGCC), are the major contributors of cold and fresh water masses to the vicinity of the study area (Bacon et al., 2002). However, the main component of these currents is deflected and turns northwards around the slope region near Cape Farewell and does not currently extend as far south as the core location (Cuny et al., 2002). Thus, modern surface water properties at the core site primarily reflect the water masses that occupy the interior of the Labrador Basin, which are more stable and less directly influenced by freshwater anomalies in the slope areas (Houghton and Visbeck, 2002).

3. Material and methods

3.1. Sample preparation

The giant piston core (Calypso) MD03-2664 was recovered during the P.I.C.A.S.S.O cruise of the R/V *Marion Dufresne* of the French Institut Polaire Paul Emile Victor (IPEV) within the framework of the International Marine Global Changes (IMAGES) program. MD03-2664 was continuously subsampled at 1-cm spacing over the 5-m long core interval (from 23.5 to 28.5 m) spanning late Marine Isotope Stage (MIS) 6 to early MIS 5d. Each sample was soaked in distilled water and shaken for 12 h in order to disperse the sediment, before they were wet sieved and separated into size fractions of >63 μm and <63 μm. The >63 μm fraction was used for selection of foraminiferal specimens for stable isotope analysis, Mg/Ca analysis, foraminiferal census counts and ice rafted debris (IRD) counts after additional dry sieving. In Figs. 2 and 6 we mark the new MD03-2664 data (this study) with filled circles, whereas previously published data from this core (Galaasen et al., 2014; Irvalı et al., 2012) are marked with open circles.

3.2. Stable isotopes

The planktonic foraminifer species *Neogloboquadrina pachyderma* (sinistral) and benthic foraminifer *Cibicidoides wuellerstorfi* were selected for stable isotope analyses ($\delta^{18}O$ and $\delta^{13}C$) to reconstruct surface and deep ocean physical and chemical properties (Fig. 2a) (Galaasen et al., 2014; Irvalı et al., 2012). *N. pachyderma* (s) was picked every 1 cm (2350–2850 cm) from the 150–250 μm size fraction (7–9 specimens per analysis), while *C. wuellerstorfi* was picked from all size fractions >150 μm (1–2 specimens per analysis). Before analyses, the foraminiferal shells were ultrasonically rinsed for 20 s in methanol to remove fine-