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Notes

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ABSTRACT

The Last Interglacial climatic optimum, ca. 128 ka, is the most recent climate interval significantly warmer than present, providing an analogue (albeit imperfect) for ongoing global warming and the effects of Greenland Ice Sheet (GIS) melting on climate over the coming millennium. While some climate models predict an Atlantic meridional overturning circulation (AMOC) strengthening in response to GIS melting, others simulate weakening, leading to cooling in Europe. Here, we present evidence from new proxy-based paleoclimate and ocean circulation reconstructions that show that the strongest warming in western Europe coincided with maximum GIS meltwater runoff and a weaker AMOC early in the Last Interglacial. By performing a series of climate model sensitivity experiments, including enhanced GIS melting, we were able to simulate this configuration of the Last Interglacial climate system and infer information on AMOC slowdown and related climate effects. These experiments suggest that GIS melt inhibited deep convection off the southern coast of Greenland, cooling local climate and reducing AMOC by ~24% of its present strength. However, GIS melt did not perturb overturning in the Nordic Seas, leaving heat transport to, and thereby temperatures in, Europe unaffected.

INTRODUCTION

The Last Interglacial (LIG; ca. 130–116 ka) represents the most recent period when North Atlantic summer climate was significantly warmer than present (Overpeck et al., 2006), and sea level was 4–9.4 m higher than today (Kopp et al., 2009). This sea-level highstand implies substantial melting of the Greenland Ice Sheet (GIS) (Northern Hemisphere ice volume is very likely to have shrunk by ≤2.6 m of equivalent sea-level volume when the loss of Arctic glaciers and ice caps is included; Otto-Bliesner et al., 2006; Colville et al., 2011) and Antarctic ice sheets (Kopp et al., 2009), suggesting a potential analogue for understanding the impact of ongoing global warming (Overpeck et al., 2006). Geochemical and magnetic runoff records from off the coast of south Greenland suggest elevated ablation and extensive GIS retreat through the LIG (Colville et al., 2011; Carlson et al., 2008); pollen concentration data indicate rapid colonization by shrub tundra following ice retreat (de Vernal and Hillaire-Marcel, 2008). This past retreat of ice sheets under a climate warmer than present allows insights into the effects of future GIS meltwater on the Atlantic meridional overturning circulation (AMOC) response and subsequent climate feedbacks. In the near surface, the AMOC transports warm and saline waters poleward across the North Atlantic, along wind- and density-driven currents. When cooling has made the waters sufficiently dense, deep convection with heat release to Europe can occur, after which the dense water masses flow equatorward as North Atlantic Deep Water. Although climate models do not show a consistent AMOC response to GIS melting (e.g., Fichefet et al., 2003; Jungclaus et al., 2006; Lunt et al., 2004; Swingedouw and Braconnot, 2007), they generally simulate North Atlantic and European cooling in response to increased freshwater forcing to the North Atlantic and the attendant reduction in AMOC strength (Stouffer et al., 2006). In contrast, the LIG was characterized by maximum development of temperate forests in Europe, the so-called Eemian interglacial, with estimated summer temperatures ~2 °C warmer than present (Kaspar et al., 2005), suggesting that the warmest LIG regional climate occurred during a period of GIS retreat. Here, we provide new insights into the impact of GIS melting on the AMOC and western European climate during the LIG.

METHODS

We present new high-resolution marine and terrestrial paleoclimatic data from a marine sediment core retrieved in the Bay of Biscay; core MD04–2845 (Sánchez Goñi et al., 2008) (Fig. 1) spans ca. 140 ka to the present. This sequence allows the establishment of a direct correlation between records of European vegetation and climate, sea-surface temperature (SST), ocean ventilation variability, and iceberg discharges, precluding the potential chronological uncertainties involved in comparing paleoclimatic records from different sites (for detailed methods, age model construction, pollen percentage diagram, and quantitative climatic reconstruction, see Figs. DR1–DR4 and Table DR1 in the GSA Data Repository[1]). These records are compared through a common age model (Table DR1) with records from the Eirik Drift off southern Greenland documenting the response of the GIS (Carlson et al., 2008) (Fig. 2). Relative changes in southern GIS ablation are reconstructed through documenting the concentration of terrestrially derived elements (i.e., Ti) in Eirik Drift sediment. For example, increased Ti deposition reflects increased sediment discharge from Greenland and thus greater runoff from ablation (Carlson et al., 2008); this has recently been further confirmed though radiogenic isotope tracing of Eirik Drift silt-sized sediment (Colville et al., 2011). To evaluate the physical consistency of our proxy-based inferences, we also investigated the impact of enhanced GIS melt on the AMOC and European temperatures with a global climate model. A full description of the simulations was provided in Bakker et al. (2011) (and in Table DR2 and Fig. DR5).

RESULTS AND DISCUSSION

After the millennial-scale ice-rafting event (Heinrich event, HE 11) (Shackleton et al., 2003) documented by a prominent ice-rafted debris (IRD) peak at 135 ± 2 ka in deep-sea core MD04–2845, the penultimate deglaciation was marked by a particularly strong and rapid warming in

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[1]GSA Data Repository item 2012185, detailed methods, age model construction, pollen percentage diagram, quantitative climatic reconstruction, and description of the simulations, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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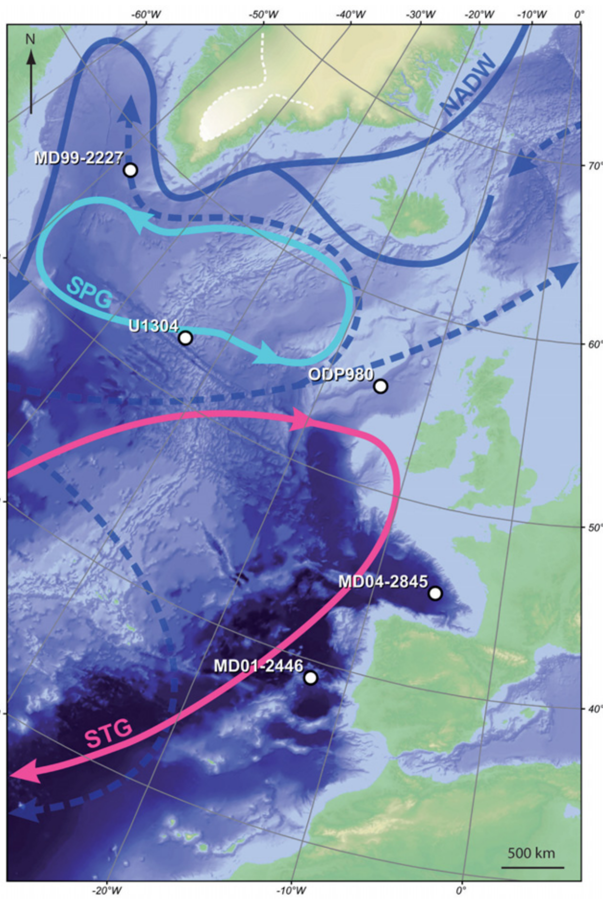

Figure 1. Location of North Atlantic and European margin sites discussed in text. STG—subtropical gyre; SPG—subpolar gyre; NADW—North Atlantic Deep Water; ODP—Ocean Drilling Program. Dashed arrows indicate North Atlantic Drift.

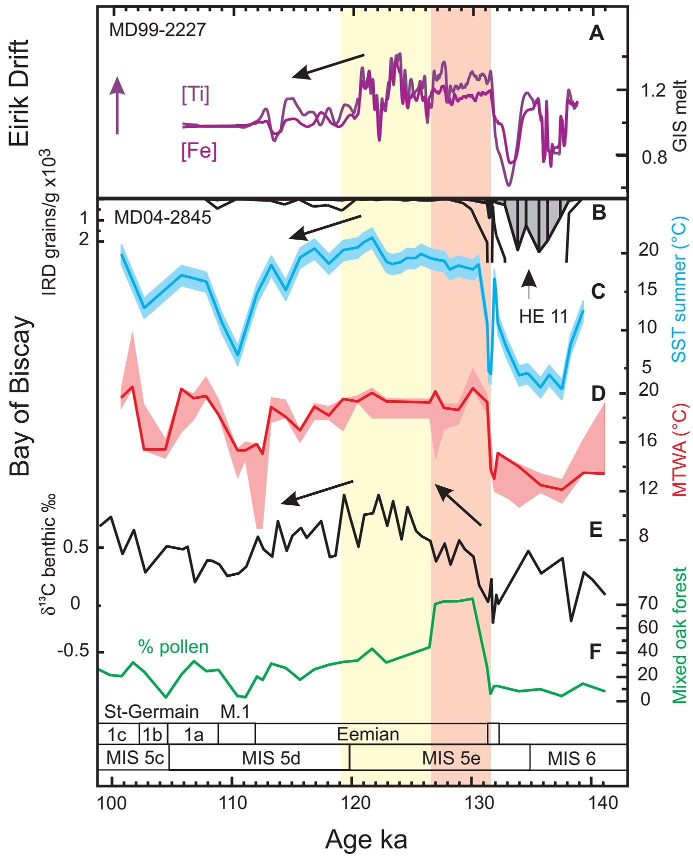

Figure 2. Paleoclimatic data for western Europe and offshore over interval 141–100 ka compared with Greenland Ice Sheet (GIS) melt changes. A: Core MD99–2227: Fe and Ti concentration curves (Carlson et al., 2008). B–F: Multiproxy study of core MD04–2845. B: Ice-rafted debris (IRD) concentration curve. HE 11–Heinrich event 11. C: Planktonic foraminifera–derived sea-surface temperatures (SST) in summer with error intervals. D: Pollen-derived summer temperatures (MTWA—mean temperature of warmest month) with error intervals. E: Benthic foraminifera δ¹³C profile. F: Pollen-inferred forest cover changes. Mixed oak forest is mainly composed of deciduous oak, hazel, ash, elm, birch and yew (Fig. DR1 [see footnote 1]). Orange band indicates European climate optimum, strongest GIS melting, and reinvigorating Atlantic meridional overturning circulation; yellow band highlights interval of sustained European warmth and GIS melting, and enhanced deep North Atlantic ventilation. M.1—Mélisey 1 cold phase; MIS—marine isotope stage.

western Europe and continued GIS runoff and ablation (Colville et al., 2011; Carlson et al., 2008) (Figs. 2A and 2B). The warming started following HE 11 with a pollen-derived 4 °C increase in western European summer temperatures contemporaneous with a 10 °C rise in summer SST (Figs. 2C and 2D). This trend was temporarily stopped by a weak and short-lived western European cold event ca. 131.4 ± 2 ka, and offshore low or minimum SSTs, as in other North Atlantic records (Oppo et al., 2006; Martrat et al., 2007). This event was synchronous with low benthic $\delta^{13}C$ values in the western European margin (Fig. 2E), similar to records from the eastern subpolar North Atlantic located on the Gardar Drift (site U1304) and the Feni Drift (site ODP980) (Oppo et al., 2006; Hodell et al., 2009) (Fig. 1), likely reflecting a decrease in regional deep ocean circulation (Oppo et al., 2006).

At 130 ± 2 ka, and contemporaneous with peak southern GIS runoff, western European temperate forest cover underwent a rapid increase (Fig. 2F), translating to an additional summer warming of ~8 °C at middle latitudes and marking the climatic optimum of the LIG (Fig. 2, orange band). Pollen data indicate that during the warmest period of the LIG, the mean temperature of the warmest month in western Europe reached values higher than 20 °C, or ~2 °C warmer than present (Fig. 2D), similar to previous estimates for the beginning of this period (Kaspar et al., 2005). The mean temperature of the coldest month also reached its warmest value at that time (Fig. DR3). In contrast, benthic $\delta^{13}C$ in our record (Fig. 2E) and elsewhere in the North Atlantic (Oppo et al., 2006; Martrat et al., 2007; Guihou et al., 2010) increased in the early LIG, but did not reach their maximal values before the middle of the LIG. A similar pattern is suggested by the $^{231}Pa/^{230}Th$ ratios, a tracer for changes in AMOC strength (Guihou et al., 2010), from cores MD01–2446 (southwest Iberian margin) (Fig. 1) and SU90–11 (west North Atlantic). Modern-like deep-water renewal is inferred over the LIG (Guihou et al., 2010), but the maximum AMOC strength, i.e., minimum $^{231}Pa/^{230}Th$ values, appears to occur in the middle of the LIG. These observations reveal a reinvigorated but not fully recovered AMOC relative to the mid-late LIG during the peak warmth in western Europe. These changes correspond within dating uncertainties with the rise to maximum Summit Greenland $\delta^{18}O$ values (Suwa et al., 2006) and peak ablation of the southern GIS (Colville et al., 2011; Carlson et al., 2008), implying the warmest summer temperatures over central and southern Greenland.

Both high $\delta^{13}C$ values and $^{231}Pa/^{230}Th$ measurements from the North Atlantic suggest that the AMOC reached peak strength in the middle of the LIG (Oppo et al., 2006; Guihou et al., 2010), when SSTs in the eastern subpolar (Oppo et al., 2006) and mid-latitude North Atlantic reached warmest temperatures ca. 123 ka, lagging the warmest temperatures by a few millennia in western Europe (Figs. 2C and 2D). This period of over-all enhanced deep North Atlantic ventilation ca. 127–119 ka corresponds with oscillating but strong GIS runoff and sustained European summer warmth, although winter temperatures cooled (Figs. 2A and 2D, yellow band; Fig. DR3). During this interval, oak mixed forest was progressively replaced by hornbeam-oak temperate forest (Fig. DR1). From ca. 119 ka onward, long-term cooling affected western Europe and the eastern North Atlantic with expansion of boreal trees and retreat of mixed oak forest cover, and long-term decrease in SSTs (Fig. DR1; Fig. 2C).

Our observations highlight two different situations: (1) strongest GIS melting ca. 131–127 ka contemporaneous with an invigorating AMOC and the warmest temperatures in western Europe (Fig. 2, orange band); and (2) sustained GIS melting ca. 127–119 ka contemporaneous with an AMOC at full strength and warm summer temperatures in Europe (Fig. 2, yellow band). GIS runoff also declined when Europe and the adjacent ocean cooled and AMOC weakened into the next ice age (Guihou et al., 2010) (Fig. 2). In contrast to the largely accepted view that accelerated meltwater input produces a weakening of the AMOC and European cooling (e.g., Fichefet et al., 2003; Swingedouw and Braconnot, 2007), we observe that the AMOC strength increased at the same time as GIS melting increased and the middle latitudes of the eastern North Atlantic and adjacent landmasses underwent warming. High boreal summer insolation, a 21 ppm increase in atmospheric CO_2 concentration (Lourantou et al., 2010), and the early disappearance of Northern Hemisphere ice sheets (Overpeck et al., 2006) ca. 130 ka can account for the particularly strong and rapid development of forest cover and the warmest temperatures in Europe during the LIG. For comparison, the increase in the pollen percentages from temperate forest growth appears to be twice as large and rapid at the onset of the LIG relative to the Holocene ca. 11.7 ka (Fig. DR4). Lunt et al. (2004) suggested that retreat of the GIS and vegetation growth could add a feedback where the attendant decrease in albedo could lead to local and downwind warming in regions such as western Europe. These mechanisms may have counterbalanced the slow reinvigoration of the AMOC and contributed to the European climate optimum and strongest GIS melt.

The physical consistency of a weak AMOC resulting from GIS melting, contemporaneous with warmer than present-day summer temperatures in Europe, is investigated using the LOVECLIM version 1.2 global climate model, described extensively by Goosse et al. (2010). We performed a range of 500-yr-long simulations with 130 ka greenhouse gas concentrations and orbital configurations that differed only in the amount of freshwater discharged from the ice sheet representing partial, but highly uncertain, GIS melting (for detailed model simulations, see the Data Repository, Table DR2 and Fig. DR5). The simulations show that if the imposed GIS freshwater flux does not exceed 0.039 Sv (1 Sv = 10^6 m^3 s^{-1}), LIG summer temperatures in southwest Europe remain higher than present day because of the positive Northern Hemisphere summer insolation anomaly, while the AMOC strength is already significantly reduced. As this climatic situation is in agreement with our proxy data–based hypothesis, we focus on the experiment with an 0.039 Sv forcing (Fig. 3B) and compare it to a 130 ka control experiment in which no additional freshwater was imposed (Fig. 3A). We note that the actual GIS melt flux in the early LIG is highly uncertain. Based on sea-level reconstructions, a maximum global melt flux of 0.29 Sv has been estimated for the early LIG (Rohling et al., 2008), but because this estimate includes all global sources, the contribution from GIS melting must have been considerably below this value. Given the uncertainties involved, from 1.6 to 5.5 m (Otto-Bliesner et al., 2006; Tarasov and Peltier, 2003; Cuffey and Brook, 2000), we argue that our imposed freshwater flux of 0.039 Sv is well within the range of possible values for the early LIG. The simulated climate for a GIS melting of 0.039 Sv shows that the sea surface around Greenland is freshened and deep convection off the coast of southeast Greenland and to north of Iceland is weakened. In combination with increased sea-ice cover, heat exchange between the atmosphere and ocean is reduced, lowering regional atmospheric surface temperatures. Despite a simulated cooling over parts of Greenland, summer temperatures over the GIS remain above present-day values. In agreement with the presented data, this model simulation suggests that GIS melt decreases the AMOC by ~24% of its full strength. However, deep convection in the Nordic Seas is not perturbed (Fig. 3B; Table DR2), leaving the North Atlantic Drift and heat transport to Europe unaffected. Given the potential analogue between LIG and the end of the 21st century (Overpeck et al., 2006), we suggest that future GIS melting in response to increasing radiative forcing and consequent North Atlantic freshening may be associated with warming temperatures in western Europe, as GIS melt is possibly incapable of counterbalancing the effects of rising anthropogenic greenhouse gas concentrations.

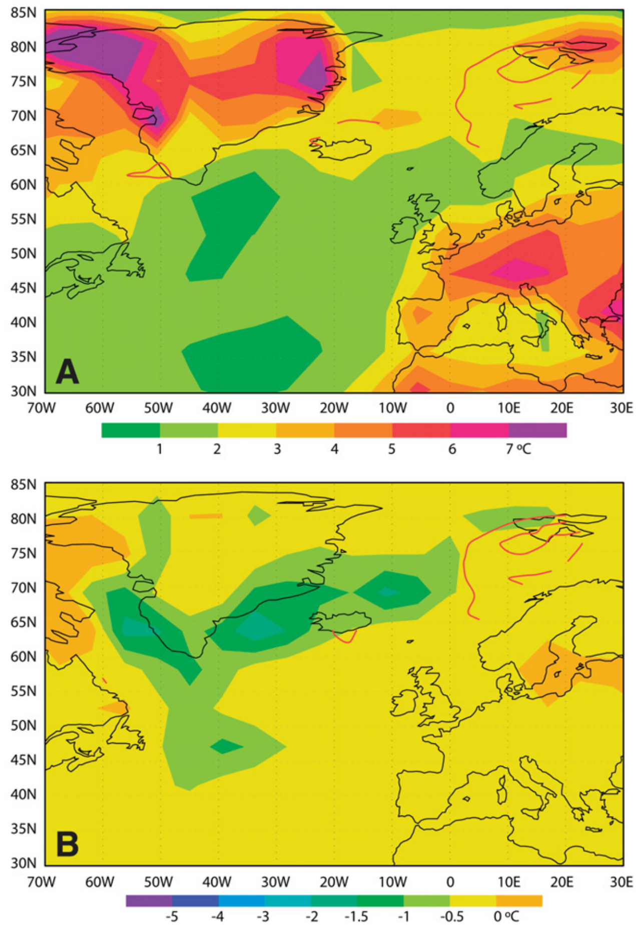

Figure 3. July surface temperature anomalies (°C) and deep-water formation sites for North Atlantic region. A: In 130 ka. B: In FWF-0.039 experiment. Reference simulations are PI and 130 ka experiments, respectively. Red contours of 750 m and 1500 m indicate maximum thickness of convective layer in ocean in February, representative of major sites of deep convection. All averages are taken over last 100 yr of simulations.

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