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Multiproxy comparison of oceanographic temperature during Heinrich Events in the eastern subtropical Atlantic

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ABSTRACT

Abrupt climate change episodes associated with catastrophic calvings of the Laurentide and European Ice Sheets during the last glacial, Heinrich Events (HE), had far-reaching effects in the Atlantic. We have measured minor and trace element concentrations in planktonic foraminiferal calcite in a core from the Iberian Margin (MD95-2040) and a core from the Gulf of Cadiz (MD99-2339) during HE 1, 4 and 5 to explore the use of the Mg–temperature proxy for constraining regional temperature changes during these unique periods of ice-rafting. High sedimentation rates throughout the length of both cores allow a detailed reconstruction of temperature during abrupt events. Mg/Ca-derived temperatures reveal ~5–13 °C amplitude of cooling during HE1, the largest and most well defined event in this region. The northern site most likely experienced the higher end of this amplitude range. Cooling implied by the Mg/Ca data is within the range of assemblage-derived sea surface temperature (SST) changes from the same cores showing ~10 °C perturbations for each HE but the Mg/Ca data imply smaller changes during HE4 and HE5. Cooling estimated from unsaturated alkenone ratios (~3 °C) represent the smallest changes. The prominence of HE1 in this region is consistent with the changes over the wider North Atlantic that show colder temperatures during HE1 vs. HE4. We use Cd/Ca to reconstruct nutrient concentrations and find very low values (0.02–0.04 μmol/mol) at both locations during HE. These low values are consistent with core top planktonic Cd/Ca from each region suggesting that the cooling during HE was unlikely to be caused by more intense upwelling than in the modern. Temperature comparisons of other proxies, alkenone ($U_{37}^{K'}$) and assemblage data, from the same core suggest that Mg/Ca paleothermometry is sensitive to the relative size of each HE. This sensitivity is capable of highlighting other variables that influence the impact of Heinrich Events on SST, including the background climate state.

1. Introduction

During the last glacial and deglacial periods, Greenland experienced rapid changes in surface air temperature (Dansgaard–Oeschger or "D–O" Events), characterized by an abrupt, decadal scale warming followed by a gradual, millennial scale cooling (Dansgaard et al., 1993; Grootes and Stuiver, 1997). The coldest stadials of these events were punctuated by catastrophic ice sheet calvings, especially of the Laurentide Ice Sheet, approximately every 7.2 kyr (Sarnthein et al., 2000). These massive calving episodes, Heinrich Events (HE), are identified by layers of ice rafted debris as far south as the northern subtropics and are associated with strong sea surface temperature fluctuations in the North Atlantic (Cortijo et al., 1997; Van Kreveld et al., 2000). The climatic significance of HE is also evidenced by far-reaching geographic locations that show correlative events along the coasts of Brazil and Florida and in the Mediterranean Sea (Arz et al., 1998; Broecker, 2006; Cacho et al., 1999; Grimm et al., 2006).

SST for HE have been derived mostly from faunal assemblage data with some additional data from alkenone $U_{37}^{K'}$ and Mg/Ca. SST estimates derived from planktonic foraminiferal assemblage data suggest that during HE, summer SSTs dropped to 3–6 °C in the subarctic North Atlantic (Chapman and Maslin, 1999; Cortijo et al., 1997) and to 5–10 °C along the Iberian Margin in the subtropical North Atlantic (de Abreu et al., 2003; McManus et al., 2004; Salgueiro et al., 2010; Schoenfeld and Zahn, 2000). A curious feature of the subtropical SSTs implied by the faunal assemblage data along the Iberian Margin is that the data imply nearly the same large cooling during each HE, despite disparate thicknesses of ice-rafted debris (IRD) layers in the North Atlantic for different HE. In contrast, the dramatic shifts in subtropical SSTs of as much as 10 °C, specifically during HE1 (~17–15 ka), HE4 (~40–38 ka) and HE5 (~47–45 ka) (de Abreu et al., 2003; Voelker et al., 2006), are not consistent with SSTs derived from alkenone $U_{37}^{K'}$ which imply little cooling during the glacial HE in this region (Bard et al., 2000; Pailler and Bard, 2002).

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Lower SSTs throughout the North Atlantic during HE are consistent, however, with modeling experiments in which freshwater released into areas of deep water formation in the North Atlantic results in a weakening, or complete shutdown of North Atlantic Deep Water (NADW) circulation (Ganopolski and Rahmstorf, 2001). Model runs that explore a range of freshwater forcing scenarios predict lower SSTs throughout the North Atlantic that vary with both the amplitude and timing of the freshwater input. The degree of North Atlantic cooling during these events and the effects on the Atlantic Meridional Overturning Circulation (AMOC) system are likely also to depend on the background climate state (Prange et al., 2004). Proxy data can help in evaluating the environmental changes associated with HE during both the glacial and deglacial states and may help to constrain sensitivity of the AMOC to the background climate.

Here, we use Mg/Ca data from planktonic foraminifera to further explore SST changes during HE. Mg/Ca has been widely applied in paleotemperature reconstructions, particularly over the last glacial cycle, but have been only looked at during HE in a limited number of studies (Peck et al., 2008; Skinner and Elderfield, 2005). Complications in applying Mg-paleothermometry, in general, are the potential influence of dissolution and salinity on shell Mg/Ca as well as the necessity for species-specific Mg–temperature equations. Dissolution is unlikely to be a major influence in the cores in this study given that both cores are located above the regional lysocline and contain well-preserved foraminifer throughout. In these two cores, shell weights per individual are high (10–14 μg), indicating well preserved specimens, however there is variation in normalized shell weight during HE1 in core MD95-2040 (see Section 4.1.1). Any potential salinity effect, however, could have a larger impact in temperature reconstructions given that HE could be accompanied by significant local salinity changes due to the melting of ice; yet, the magnitude of the salinity effect on Mg/Ca is not well defined. Here we deal with uncertainties in the Mg–temperature relationship, including salinity, by using multiple calibration equations to constrain a range of temperatures and compare the range to other temperature proxies. We derive one of the calibration equations from published core top data for the North Atlantic.

Comparing new foraminiferal minor and trace element data to the suite of existing paleoceanographic proxy data including foraminiferal $\delta^{18}O$, assemblage data and alkenone $U^{K'}_{37}$ during HE1, HE4 and HE5 in this region helps to constrain the climate fluctuations during HE. We use a published ~15 ka record of Mg/Ca variability from the same region to put the temperature changes during HE into the context of climate variability during the last glacial and deglacial (Skinner and Elderfield, 2005). We also compile SST proxy data for HE1 and HE4 to develop a better picture of the impact of these two events in the broader North Atlantic. Finally, we present the first measurements of planktonic Cd/Ca from HE. We investigate whether planktonic Cd/Ca, a proxy for nutrient concentration, shows evidence for changes in upwelling, which is one mechanism by which SSTs could change among the coastal records as well as in comparison to changes in the North Atlantic, more generally, during HE.

We show that, in this region, each temperature proxy implies different amplitudes of change during Heinrich Events. Despite the differences among the proxies, the dominant trend among the proxy data suggests that the climate changes in the North Atlantic were larger during HE1, which occurs over the transition from glacial to interglacial, than during HE4 and HE5, which are solidly in the glacial. Temperature changes in the coastal region we examine here appear to have been larger than changes in the open ocean during both HE1 and HE4, but are unlikely to be attributed to more intense coastal upwelling.

2. Methods

2.1. Core locations, age models and sampling

We obtained samples from two cores, MD95-2040 (40.58°N, 9.86°W; 2465 m) along the western Iberian Margin (the northwest margin) and MD99-2339 (35.88°N, 7.53°W; 1170 m) along the southern Iberian Margin, in the Gulf of Cadiz (Fig. 3). Analysis of these IMAGES project sediment cores reveals IRD during each of the five most recent HE, indicating the presence of icebergs in this region (de Abreu et al., 2003; Voelker et al., 2006). The presence of IRD allows tight correlation of regional oceanographic changes with the Heinrich Events.

Sample depths from cores MD95-2040 and MD99-2339 were converted to age using published age models (Salgueiro et al., 2010; Voelker et al., 2006). In both cores, Heinrich Events were sampled to yield a resolution of ~250 yr, which was approximately every 9 cm in core MD95-2040 and every 6 cm in core MD99-2339. Average sedimentation rates during each HE at site MD95-2040 were calculated to be 30–40 cm/kyr, while between HE sedimentation rates were approximately 20 cm. Sedimentation rate at site MD99-2339 during HE ranges from 30 to 45 cm/kyr and outside of HE ranges anywhere from 20 to 70 cm/kyr. Modern Mg/Ca-based SSTs are reconstructed from surface samples near each of the core sites (Salguiero et al., in prep).

To provide additional context for the Mg/Ca variations we report for HE in this region, we plot our Mg/Ca data from HE1 from MD95-2040 and MD99-2339 with a published high resolution *Globigerina bulloides* record from core MD99-2334 (37°47′N, 10°10′W, 3146 m; Skinner and Elderfield, 2005) for 10 ka to 22 ka. Mg/Ca for *G. bulloides* data are presented graphically versus depth in Skinner and Elderfield (2005). We plot the data using a published age model for core MD99-2334 based on radiocarbon dates to convert depths to ages (Skinner and Shackleton, 2004).

2.2. Samples and sample preparation

Our reconstructions in both cores are based on the planktonic species, *G. bulloides*. Analysis of surface sediment data suggest that *G. bulloides* are related to upwelling and thus most abundant during summers in this region (Salgueiro et al., 2008). *G. bulloides* are present throughout the length of core MD95-2040 (de Abreu et al., 2003), however, small available sample sizes prevented replicate analyses. The site of MD99-2339 recorded a more diverse planktonic foraminifera fauna than core MD95-2040 and abundance of specific species varied significantly between HE (Voelker, unpubl. data). Although scarce in most of the core, *G. bulloides*, makes up approximately 50% of the planktonic assemblage during HE (Voelker, unpubl. data). In core MD99-2339, we combined intervals prior to and after HE (i.e. intervals with low abundance of *G. bulloides*) with one or two adjacent depths to yield samples large enough to clean and analyze. Samples from combined intervals before and after HE have inconsistent resolution and span, on average, 10 cm (200–500 yr).

Approximately 30 individual *G. bulloides* were picked from the 255–350 μm size fraction of disaggregated sediment yielding sample sizes between 0.3 and 0.4 mg. Samples from both cores were crushed before cleaning for trace element analysis such that the inner chamber walls were exposed. Any obvious mineral contaminants were removed. Cleaning followed the protocol of Boyle (1981) with modifications as outlined in Lea and Martin (1996). The method involves 5 steps: n-pure and methanol rinses, reduction to remove authigenic contaminants, oxidation to remove organics, heating and final acid leach. The cleaning procedure was modified for samples ~0.1 mg. Samples of this size are one third of the optimal weight for which the standard cleaning protocol is designed. A significant amount of sample is lost during the reduction step; therefore, for small samples, we reduced the amount of buffered hydrazine in the reduction step to 33 μl instead of the typical 100 μl (Bian and Martin, 2010).

After cleaning, samples were dissolved in a spiked acid solution and analyzed by single collector magnetic sector-ICPMS to determine trace metal to Ca ratios at the analytical lab of the Marine Science Institute at the University of California, Santa Barbara, following a method similar to that outlined in Lea and Martin (1996) for Quadrapole ICP-MS but modified for the magnetic sector instrument. In addition to Mg/Ca,