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Enhanced Mediterranean-Atlantic exchange during Atlantic freshening phases

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[1] The Atlantic-Mediterranean exchange of water at Gibraltar represents a significant heat and freshwater sink for the North Atlantic and is a major control on the heat, salt and freshwater budgets of the Mediterranean Sea. Consequently, an understanding of the response of the exchange system to external changes is vital to a full comprehension of the hydrographic responses in both ocean basins. Here, we use a synthesis of empirical (oxygen isotope, planktonic foraminiferal assemblage) and modeling (analytical and general circulation) approaches to investigate the response of the Gibraltar Exchange system to Atlantic freshening during Heinrich Stadials (HSs). HSs display relatively flat W–E surface hydrographic gradients more comparable to the Late Holocene than the Last Glacial Maximum. This is significant, as it implies a similar state of surface circulation during these periods and a different state during the Last Glacial Maximum. During HS1, the gradient may have collapsed altogether, implying very strong water column stratification and a single thermal and $\delta^{18}O_{water}$ condition in surface water extending from southern Portugal to the eastern Alboran Sea. Together, these observations imply that inflow of Atlantic water into the Mediterranean was significantly increased during HS periods compared to background glacial conditions. Modeling efforts confirm that this is a predictable consequence of freshening North Atlantic surface water with iceberg meltwater and indicate that the enhanced exchange condition would last until the cessation of anomalous freshwater supply into to the northern North Atlantic. The close coupling of dynamics at Gibraltar Exchange with the Atlantic freshwater system provides an explanation for observations of increased Mediterranean Outflow activity during HS periods and also during the last deglaciation. This coupling is also significant to global ocean dynamics, as it causes density enhancement of the Atlantic water column via the Gibraltar Exchange to be inversely related to North Atlantic surface salinity. Consequently, Mediterranean enhancement of the Atlantic Meridional Overturning Circulation will be greatest when the overturning itself is at its weakest, a potentially critical negative feedback to Atlantic buoyancy change during times of ice sheet collapse.

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1. Introduction

[2] The Mediterranean-Atlantic exchange through the Strait of Gibraltar dominates the heat, salt, mass, and energy budgets of the Mediterranean Sea [*Bethoux*, 1979; *Bryden and Stommel*, 1984] and provides a major influence on eastern North Atlantic circulation at depths <2000 m close to 35°N [*Özgökmen et al.*, 2001] and at intermediate depth (500–1500 m) throughout much of the midlatitude North Atlantic [*Iorga and Lozier*, 1999]. As the Gibraltar Exchange effectively replaces North Atlantic Central Water with relatively cold and salty Mediterranean Outflow Water [*Bryden and Stommel*, 1982; *Garcia-Lafuente et al.*, 2009], it is an important heat and freshwater sink, promoting and sustaining deep convection in the Nordic Seas [*Bigg et al.*, 2003]. The export of buoyancy from the Atlantic caused by the Gibraltar Exchange does not seem to be a dominant control on the relatively vigorous meridional convection of today [*Rahmstorf*, 1998] but is anticipated to be of far greater importance during phases of slow or stagnant convection in the Arctic [*Rogerson et al.*, 2006a]. Consequently, it is vital to constrain the flux and properties of the water masses exchanged at Gibraltar in the past, and given that the exchange is primarily driven by the Mediterranean-Atlantic salinity gradient [*Bryden et al.*, 1988], it is particularly important to constrain the behavior of the exchange during phases of Atlantic freshening.

[3] One of the most characteristic and widely investigated features of the last glacial cycle in the North Atlantic are the Heinrich Events [*Bond et al.*, 1993; *Broecker*, 2000; *Chapman et al.*, 2000; *Heinrich*, 1988]. These are layers with abundant

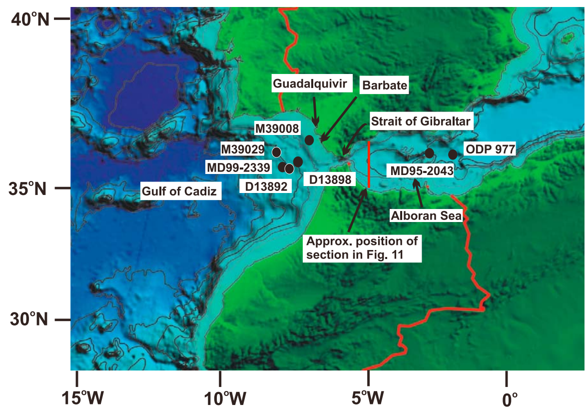

Figure 1. Map of the region of study, showing the locations of cores discussed.

sand-sized Ice Rafted Debris (IRD), transported by iceberg armadas from the North American [*Andrews*, 1998] and/or Greenland and European [*Grousset et al.*, 2000] ice sheets. Critically for this study, most reconstructions of conditions during Heinrich Events describe anomalous surface water freshening over an extensive area of the northern North Atlantic (see review by *Hemming* [2004]), certainly sufficient to affect the Gibraltar Exchange [*Rogerson et al.*, 2008].The layer of reduced salinity that developed at the surface of the northern North Atlantic due to iceberg meltwater input also caused a reduction of deep-water formation [*Gherardi et al.*, 2005; *McManus et al.*, 2004; *Seidov and Maslin*, 1999; *Stanford et al.*, 2006; *Vidal et al.*, 1999], as well as promoting cold, arid conditions ("Heinrich Stadials") over the adjacent continents [*Grimm et al.*, 1993; *Rohling et al.*, 2003].

[4] In spite of the strong research focus on Heinrich Stadials, the southern limit of iceberg penetration across the North Atlantic remains incompletely constrained [*Thouveny et al.*, 2000; *Watkins et al.*, 2007]. Intervals containing significant amounts of Ice Rafted Debris have been found in marine sediment cores from the Portuguese Margin [*Baas et al.*, 1998; *Cayre et al.*, 1999; *Eynaud et al.*, 2009; *Grousset et al.*, 2000; *Lebreiro et al.*, 1996; *Schönfeld and Zahn*, 2000; *Thomson et al.*, 1995; *Thouveny et al.*, 2000], but IRD is rare in the Gulf of Cadiz, between Iberia and Morocco [*Cacho et al.*, 2001; *Llave et al.*, 2006; *Voelker et al.*, 2006]. The southernmost record of Ice Rafted Debris is at 33.5°N off the Moroccan margin [*Kudrass*, 1973]. The rapid drop-off of Ice Rafted Debris concentrations along the Iberian margin suggests that the southern limit of significant iceberg activity resided close to 35°N, the approximate position of the Azores Front during glacial times [*Rogerson et al.*, 2004; *Schiebel et al.*, 2002]. This concept is supported by numerical modeling efforts, which indicate focused melting of European-sourced icebergs on the southwest Iberian margin [*Levine and Bigg*, 2008]. A synthesis of the impact of freshening during Heinrich Stadials on the western Iberian margin is given by *Eynaud et al.* [2009], who indicate that the Polar Front lay off northern Iberia during Heinrich Stadials 1 and 4 and that surface water along the entire Iberian margin was cooled and freshened. The potential impact of this freshening is significant for regional circulation, impeding vertical and promoting lateral flow of water masses [*Eynaud et al.*, 2009].

[5] Although *Sierro et al.* [2005] inferred from stable oxygen isotope ratios in planktonic foraminifera that surface water of reduced salinity was advected from the Atlantic into the Mediterranean through the Strait of Gibraltar, no IRD has been found on the Mediterranean side of the Strait, so that icebergs themselves do not seem to have entered the Mediterranean. In other words, no Heinrich Event sensu stricto (defined by IRD) has been found within the Mediterranean. To describe the incursions of reduced-salinity, cold (as defined by alkenone paleothermometry [*Cacho et al.*, 1999, 2001]) surface water through the Strait of Gibraltar at the time of Heinrich Events in the North Atlantic (i.e., during Heinrich Stadials), we therefore define the term "Alboran Freshening Event" (AFE). We need to introduce this new term to allow differentiation of the consequences for Mediterranean hydrology of the freshened surface water inflow (the focus of this study) from the climatic impacts of the Heinrich Stadials proper (as described, for example, by *Bar-Matthews et al.* [1999] and *Rohling et al.* [1998]).

[6] Arid conditions within the Mediterranean basin result in a net evaporative loss (termed "excess evaporation," X_{med}) from the Mediterranean surface waters of 52–66 cm year^{-1} [*Bryden et al.*, 1994; *Garrett et al.*, 1993], which causes salinity to be higher in the Mediterranean water mass than in the adjacent Atlantic [*Bryden and Kinder*, 1991]. This results in a distinct interface between relatively high and low salinity water within the narrow and shallow bottleneck of the Strait of Gibraltar [*Bryden et al.*, 1994] (Figure 1). The interaction of dense Mediterranean subsurface waters with relatively buoyant North Atlantic Central Water (NACW) on either side of the Strait of Gibraltar drives a two-layer exchange [*Bryden et al.*, 1988]. Modified Atlantic Water (MAW) flows into the western Mediterranean at the surface and Levantine Intermediate Water with a minor admixture of western

Mediterranean Deep Water [*Kinder and Parrilla*, 1987] flows as a bottom layer into the Atlantic, forming the Mediterranean Outflow Water (MOW) [*Bryden et al.*, 1994; *Kinder et al.*, 1988; *Millot et al.*, 2006; *Stommel et al.*, 1973].

[7] The two-layer structure of the Gibraltar Exchange dominates circulation within the adjacent Gulf of Cadiz and Alboran Sea (Figure 1) [*Lacombe and Richez*, 1982]. Superimposed on this structure, significant tidal, annual and meteorologically produced sub-inertial (i.e., short wavelength) variations occur [*Bormans et al.*, 1986; *Candela et al.*, 1989; *Garrett et al.*, 1990; *Millot*, 2008; *Tsimplis and Bryden*, 2000]. These influences combine to cause the surface circulation to attain one of three circulation states [*Folkard et al.*, 1997] which occur in (1) the summer under easterly winds, (2) the summer under westerly winds, and (3) the fall-winter-spring. During prevalence of circulation pattern 1, the central Gulf of Cadiz displays colder SST than the Alboran Sea, whereas the Gulf of Cadiz is warmer than the Alboran Sea during the other two circulation patterns [*Folkard et al.*, 1997]. At all times, minimum SST is found within the Strait of Gibraltar, due to local upwelling of MOW on the eastern side of the shallowest section, the Camarinal Sill [*Folkard et al.*, 1997].

[8] Seasonally, sea surface salinity varies by less than 0.5 within the Gulf of Cadiz [*MEDATLAS*, 2002], and it is thus justified to assume a constant annual base-line value of 36.5 for the present-day configuration. Similarly, we assume single annual base-line values for surface salinity in the Alboran Sea (37.3) and in the MOW (38.5) [*MEDATLAS*, 2002]. Simple two-end-member mixing can be invoked to explain the ~0.8 offset between Gulf of Cadiz and Alboran Sea surface salinity values, indicating a 42 ± 8% admixture of upwelled MOW water, varying slightly seasonally. The upwelling within the Strait of Gibraltar also affects the offset in SST between the Gulf of Cadiz and Alboran Sea described in the previous paragraph. This influence varies seasonally due to smaller difference between winter SST in the Gulf of Cadiz (~16.6°C) and MOW temperature (~12.9°C, which varies only slightly seasonally [*Tsimplis and Bryden*, 2000]), compared to that between Gulf of Cadiz summer SST (~22.6°C) and MOW temperature [*MEDATLAS*, 2002].

[9] As the Gibraltar Exchange is known to have been active during Heinrich Stadials and the Last Glacial Maximum (LGM) [*Rogerson et al.*, 2006a; *Voelker et al.*, 2006], the basic pattern of surface exchange outlined above would have been similar, leading to rapid west to east transit of Atlantic sourced hydrographic signals. Consequently, any change on the Atlantic side of the Strait of Gibraltar will be transmitted to the Alboran Sea within years or decades, well below the resolution of most marine paleoceanographic records. Consequently, major hydrographic transitions (such as incursion of IRD, or strong cooling) can be correlated across the region with a high degree of confidence, and the Heinrich Events, though necessarily slightly pre-dating AFE's, can practically be assumed to be coincident with them. Here, we use empirical records of sea surface conditions combined with modeling to test what impact AFE's had on the Gibraltar Exchange, and thus on the balance of freshwwater, salt and heat transport between these basins.

2. Methods

2.1. Synchronization of Records

[10] We use ten records from eight locations, representing most of the well-dated, high resolution records from the transect area, which together provide good coverage of the Gibraltar region. All of the records used in this study have independent age models, with extensive AMS ^{14}C chronostratigraphic control (for original sources see Table 1). However, to facilitate comparison between the various records, it is necessary to confirm that the key periods under investigation are synchronous in the records and that events such as the Heinrich Stadials were not time-transgressive. We thus define a single standard chronology, for which we selected MD95-2043 from the Alboran Sea [*Cacho et al.*, 1999; *Sierro et al.*, 2005] on the basis of its exceptional coherence with the GISP2 Greenland ice core major ion series [*Rohling et al.*, 2003] and the fact that this core lies at the down-stream limit of North Atlantic-sourced freshening pulses. Only Heinrich Stadial 1 and Heinrich Stadial 2 are investigated here, as older events were reached by only a few cores. Full chronological "tuning" of the records is not necessary for our assessment, as our analysis requires only that Heinrich Stadials 1 and 2 are regionally synchronous. To determine the position of these events within the core records, we use significant changes in surface temperature, ecology or the occurrence of IRD as proxy markers; the bases of the assignment of the position of HS1 and 2 in individual cores are summarized in Table 1. We use a broad definition for the LGM, defining it as the period between the

Table 1. Information on Cores Studied

Core	Lat	Long	Data Used	Age HS1: In Source Age Model (ka BP)	Age HS1: Change During Tuning to MD95-2043 (ka): Onset	Age HS1: Change During Tuning to MD95-2043 (ka): End	Age HS2: In Source Age Model (ka BP)	Age HS2: Change During Tuning to MD95-2043 (ka): Onset	Age HS2: Change During Tuning to MD95-2043 (ka): End	Basis of Assignment	Original Source
ODP-977A	36.03	−1.95	Planktonic foraminiferal assemblage, ANN-SST, $\delta^{18}O_{G. bulloides}$	17.1–15.2	−0.4	0	~23.8	Date of center falls within range		Maxima in *N. pachyderma* (s) %	*Pérez-Folgado et al.* [2003]
MD95-2043	36.14	−2.69	Planktonic foraminiferal assemblage, ANN-SST, $\delta^{18}O_{G. bulloides}$	16.7–15.2	N/A	24.2–23.9		N/A	N/A	Maxima in *N. pachyderma* (s) %	*Cacho et al.* [1999], *Pérez-Folgado et al.* [2003], *Schönfeld and Zahn* [2000], and *Sierro et al.* [2005]
M39008-3	36.38	−7.07	$\delta^{18}O_{G. bulloides}$	~16.2	Date of center falls within range			N/A	N/A	Minimum in alkenone SST	*Cacho et al.* [2001]
D13898	35.90	−7.41	Planktonic foraminiferal assemblage, ANN-SST, $\delta^{18}O_{G. bulloides}$	16.4–15.4	0.3	−0.2	23.9–23.1	0.3 ka	0.8 ka	Maxima in $\delta^{18}O_{G. bulloides}$ and % *T. quinqueloba*	*Rogerson et al.* [2004]
D13892	35.78	−7.72	Planktonic foraminiferal assemblage, ANN-SST, $\delta^{18}O_{G. bulloides}$	16.2–15.8	0.5	−0.6	N/A	N/A	N/A	Presence of IRD and maxima in % *T. quinqueloba*	*Rogerson et al.* [2006b]
MD99-2339	35.89	−7.88	Planktonic foraminiferal assemblage, $\delta^{18}O_{G. bulloides}$	17.3–15.2	−0.6	0	26 - 24.6	−1.8 ka	−0.7 ka	Presence of IRD and maxima in *N. pachyderma* (s) %	*Voelker et al.* [2006]
M39029-4, −7, and −8	36.04	−8.23	Planktonic foraminiferal assemblage, ANN-SST, $\delta^{18}O_{G. bulloides}$	17.2–15.9	−0.5	−0.7	25.1–23.6	−0.9 ka	0.3 ka	Presence of IRD and maxima in *N. pachyderma* (s) %	*Colmenero-Hidalgo et al.* [2004], *Löwemark and Werner* [2001], and *Löwemark and Schafer* [2003]

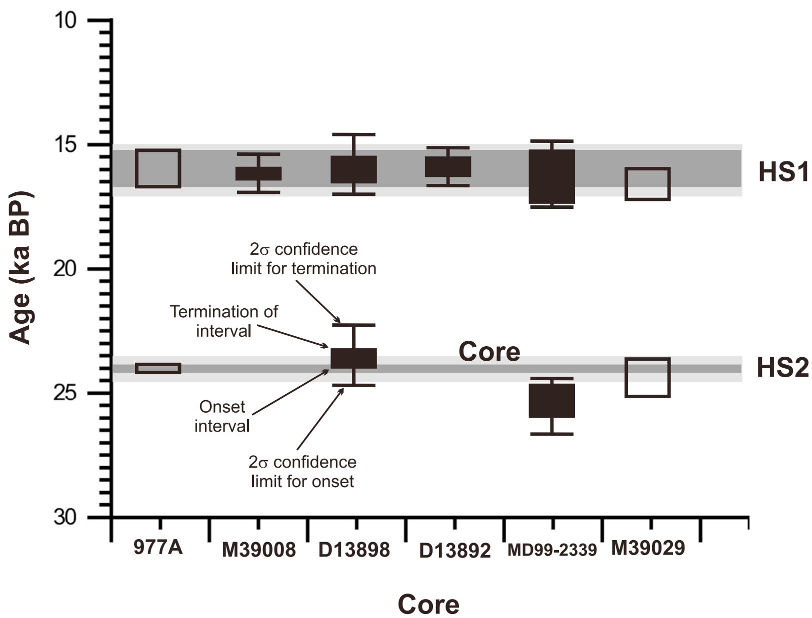

Figure 2. Compilation of age designations for Heinrich Stadials 1 and 2 within the cores used in this study. Horizontal dark gray bar represents the interval of Heinrich Stadials within MD95-2043 (i.e., in the target chronology), and light gray areas represent the 2σ errors in the designation of the onset and termination of each event. Black rectangles represent the interval of Heinrich Stadials within each chronology, with filled rectangles representing chronologies built on independent ^{14}C datings. The 2σ errors for the onset and termination are shown as bars above and below the rectangle. Unfilled rectangles represent chronologies built on correlation (see original sources in Table 1 for details).

Heinrich Stadial 1 and Heinrich Stadial 2 peaks of Arctic planktonic foraminiferal species and/or IRD. This makes age determination of this period solely dependent on accurate recognition of regionally synchronous Heinrich Stadials, also allowing analysis of mean conditions during this period without further chronostratigraphic analysis being necessary.

[11] Figure 2 shows the age assignment of HS1 and HS2 within the records as identified within the original published chronostratigraphic models of the records. To assess the degree of error in age assignments (shown as bars above and below the interval of the HS events within the core records in Figure 2), the original AMS ^{14}C datings were recalibrated to calendar age using the OxCal software, the IntCal04 atmospheric isotope curve and a 400 year reservoir age. Linear interpolation of the 2σ confidence intervals of ^{14}C radiocarbon dates then provides a means of assessing the approximate magnitude of the dating error for any point within the chronostratigraphy of the record (for further information on this approach, see the chronostratigraphic discussion by *Rogerson et al.* [2005]).

[12] Figure 2 indicates that datings for HS1 have an excellent degree of agreement across the range of the locations used within this work, confirming that this is an isochronous event and it is justified to assume that conditions during this period can be reconstructed as a discrete time-slice. HS2 shows a higher degree of scatter, as would be expected for an older event, and MD99–2339 shows an age for HS2 significantly different from MD95-2043. However, this may be a consequence of deviation of sedimentation rate in this core from the linear interpolation of the ^{14}C-based chronostratigraphic model, as HS2 is constrained only by ^{14}C determinations at 19.039 and 28 cal. ka BP. It should be noted that the original publication of the MD99–2339 record [*Voelker et al.*, 2006] incorporated an additional age constraint at 23.8 ka BP using the *N. pachyderma* (s) maximum associated with HS2, implicitly assuming that there has been some drift from linearity in the accumulation rate through this interval.

[13] The high degree of synchronicity between these records for HS1 gives high confidence that a genuine time-slice can be created for paleohydrographic analysis, and that we will not be collapsing a diachronous event into a single scenario. Notwithstanding the deviation in MD99–2339, we will also assume synchronicity for HS2 and recon-

struct this as a time-slice as well. Differences in sampling resolution, difficulties of precise submillennial-scale correlation and uncertainty regarding the precise timing and occurrence of single or multiple meltwater pulses within each Heinrich Stadial prevent compilation of data for "peak" conditions. Consequently, we determine (and use) the mean value of each record for Heinrich Stadial 1, Heinrich Stadial 2, and the LGM interval. We further use core top data as a means of representing the system during the late Holocene for comparison of proxy and modern hydrographic data.

2.2. Compilation of Microfossil and Geochemical Data Sets

[14] The majority of data used has been previously published, except for the planktonic foraminiferal fauna from cores M39029–7 and MD99–2339 and the new SST estimates based on planktonic foraminiferal assemblages. SSTs were reconstructed with the Artificial Neural Network (ANN) method [*Malmgren et al.*, 2001], using the MARGO-project database for the Atlantic [*Kucera et al.*, 2005]. This database was selected due to the location of the Mediterranean cores, as western Alboran Sea surface water is essentially Atlantic surface water giving plankton assemblages more affinity to modern Atlantic locations than modern eastern Mediterranean ones. Moreover, initial investigations revealed that estimates of SST were similar regardless of the database used, especially in the case of samples from Heinrich Stadial 1. Values represent the mean of 10 simulations, with samples where the standard deviation exceeded 1 discarded. Data sources are summarized in Table 1, and original $\delta^{18}O_{G.\ bulloides}$ and relative abundance records of *Neogloboquadrina pachyderma, Turborotalita quinqueloba* and *Globigerinoides ruber* are presented in Figures 3 and 4, respectively. Three $\delta^{18}O_{G.\ bulloides}$ records are available for M39029 (cores −4, −7 and −8): all three are presented in Figure 3, but a single set of average values is used to represent this site for later analyses.

2.3. One-Dimensional Modeling of the Gibraltar Exchange

[15] To minimize the number of assumptions needed, we use a straightforward representation of the Gibraltar exchange, which employs a hydraulic control model in combination with mass and salt conservation statements. The model assumes that the transports are maximal, i.e., that the two-layer Froude number ≥1 [*Bryden and Kinder*, 1991]. This model is represented by

$$Q_{total} = C\frac{W_s D_s}{2}\sqrt{\frac{g\beta\Delta S_{gib} D_s}{\rho_{med}}} \qquad (1)$$

where Q_{total} determines the two-way exchange across the sill (Q_{atl}-Q_{med}, where Q_{med} is a negative vector term), ΔS_{gib} is the vertical salinity difference between layers within the Strait, W_s and D_s are the width and depth at the sill, C is a constant depending on sill geometry (= 0.28 [after *Bryden and Kinder*, 1991]), g = 9.81 m s^{-2}, β is a coefficient used to convert ΔS_{gib} to $\Delta\rho_{gib}$ (β = 7.7 × 10^{-4} g cm^{-3}ppt^{-1} [after *Bryden and Kinder*, 1991]), and ρ_{med} is density of the outflowing Mediterranean water.

[16] While *Rohling and Bryden* [1994] have previously explored the *Bryden and Kinder* [1991] model under glacial to late Holocene boundary conditions, we here expand the discussion to include the specific conditions of Heinrich Stadials. To do this, we first define a background scenario that approximates exchange conditions during the LGM. The baseline values for this LGM background scenario assume sea level to be 100 m lower than present (which is taken to be a value representative of both Heinrich Stadials under investigation [*Peltier and Fairbanks*, 2006; *Siddall et al.*, 2003]), net evaporative flux (X_{med} in equation (1)) to be the same as the modern value (0.05 Sv) [*Bryden and Stommel*, 1984; *Bryden et al.*, 1988; *Tsimplis and Bryden*, 2000] and ΔS_{gib} and Q_{total} are 3.46 and 0.97 Sv respectively [*Rogerson et al.*, 2006a; *Rohling and Bryden*, 1994]. This provides a realistic context against which we can explore the impact of changing those variables that might be altered by the occurrence of the regional drying and surface water freshening associated with Heinrich Stadials in this region [*Sierro et al.*, 2005; *Tzedakis*, 2007]. Three parameters are selected for investigation relative to the background LGM scenario, namely sea level, the Mediterranean freshwater export flux (X_{med}) and the vertical salinity contrast within the Strait of Gibraltar (ΔS_{gib}). As it is still a matter of debate to what extent sea level changed [*Hemming*, 2004; *Roche et al.*, 2004; *Rohling et al.*, 2004; *Siddall et al.*, 2003] and to what extent Mediterranean freshwater export may or may not have changed through Heinrich Stadials [*Rohling*, 1999; *Tzedakis*, 2007], we investigate these influences separately.

[17] One aspect of the system that is not addressed via this simple representation is the way excess

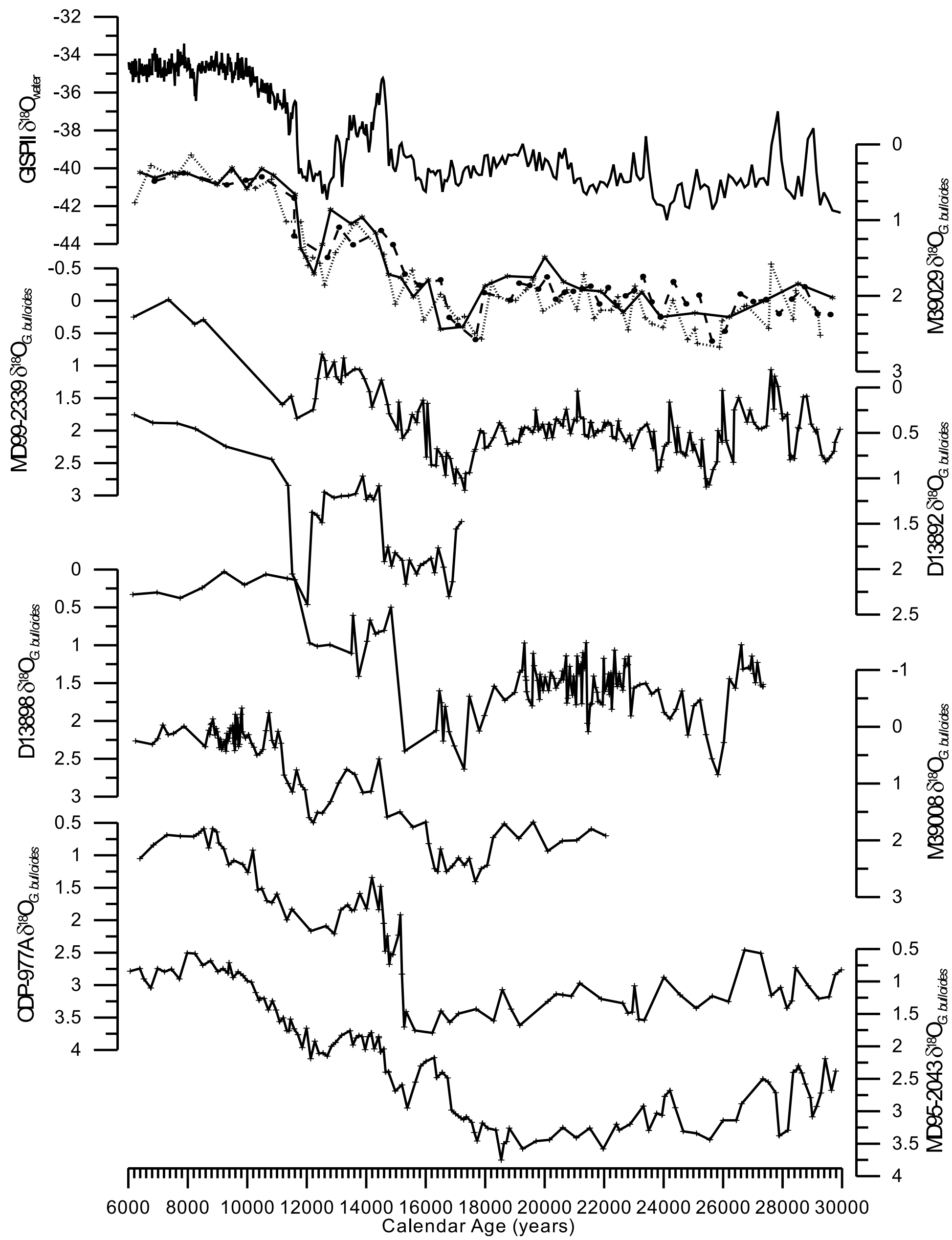

Figure 3. Compilation of $\delta^{18}O_{G.\ bulloides}$ for cores studied. Note three records for location M39029 shown as solid, dashed and dotted lines.

Mediterranean salinity will be purged under enhanced exchange conditions. ΔS_{gib} may be expected to decline over the period of freshened water supply, forcing a gradual decrease in Q_{total}. Consequently, the behavior of the 1D modeling described above must be assumed to reflect conditions during the first decades to centuries of the AFEs only, and more sophisticated modeling is required for a fully functional understanding of the Mediterranean response to Atlantic freshening to be developed.

2.4. General Circulation Modeling

[18] General Circulation Model (GCM) results are obtained using an LGM setup [*Levine and Bigg*, 2008] of a global ocean GCM that is coupled to a simple energy balance atmosphere. The ocean component of the model is described by *Wadley and Bigg* [1999], and uses a curvilinear coordinate system [*Madec and Imbard*, 1996]. The horizontal model grid emphasizes the North Atlantic deep-water formation areas around the Nordic Seas,

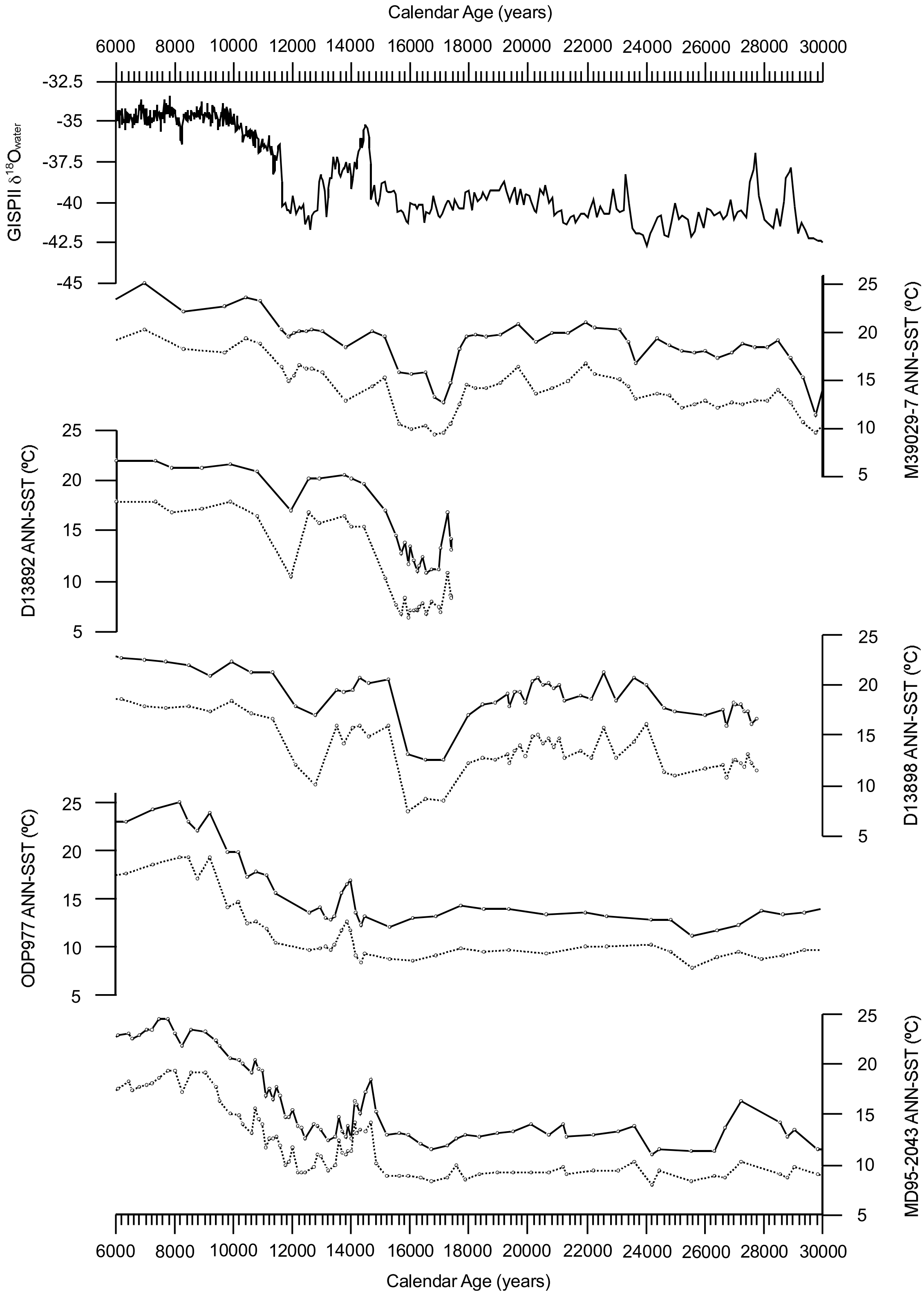

Figure 4. Compilation of ANN-SST records for cores from which planktonic foraminiferal data are available. Black and dotted lines represent summer and winter values, respectively.

where the resolution is 1°–2°, while the Southern Hemisphere resolution is 6°–8°. The ocean has 19 levels in the vertical, varying in thickness from 30 m near the surface to 500 m at depth, and has a free surface formulation for the barotropic model [*Webb*, 1996]. The ocean model is coupled to a simple radiative, advective atmosphere, which consists of the energy moisture balance model used in the UViC Earth Systems model [*Fanning and Weaver*, 1996], with the addition of advection of water vapor. The GCM is adapted for the glacial simulations with global ice sheet cover from *Peltier* [1994], and by adjusting sea level, orbital parameters, and CO_2 levels for the LGM (21 ka BP) period. The surface fluxes of heat and freshwater are determined from ocean-atmosphere interaction, while the atmospheric wind stress has an annual cycle [cf. *Dong and Valdes*, 1998]. A dynamic and thermodynamic iceberg trajectory model is also coupled to the ocean model, for both the control run and for simulations of Heinrich events [*Levine and Bigg*, 2008]. The performance of the model is discussed more fully by *Levine and Bigg* [2008], but for the present-day North Atlantic the sea surface properties compare reasonably well with the climatological values, although the gradients associated with the Gulf Stream are not fully resolved. The net Atlantic overturning strength is too high at ~28 Sv (observed values are ~18.7 ± 5.6 Sv [*Cunningham et al.*, 2007]) but much of this excess is contained within an unrealistically strong, but spatially limited, North Atlantic cell, and the export fluxes out of the North Atlantic of ~15 Sv are similar to observations [*Gordon*, 1986; *Schmitz*, 1995]. The exchange through the Strait of Gibraltar is similar to the observational value of ~1 Sv [*Bryden et al.*, 1994].

[19] For the glacial state, the coupled model was run until it reached a steady state that is reasonably consistent with paleo-observations, with North Atlantic Deep Water being found at intermediate depths [*Weinelt et al.*, 1996]. The glacial overturning rate is reduced to ~10 Sv, while the flux through the Strait of Gibraltar is ~2 Sv. This is different to the analytical model, which predicts glacial Q_{total} to be reduced relative to today, because of low spatial resolution in the Strait of Gibraltar. The GCM tends to be too cold in the northern Atlantic; there is an ice-covered Nordic Sea but paleo-observations suggest this was seasonally ice-free [*Kucera et al.*, 2005].

[20] Heinrich Events are simulated by releasing a large flux of freshwater locally from the Hudson Strait for a period of 500 years. A flux of 0.4 Sv is chosen to ensure a complete collapse of the Atlantic overturning circulation, which occurs within 20 years. This is similar to, but a little higher than, existing flux estimates [*Roche et al.*, 2004]. We also carried out a simulation where the same flux of freshwater was released in the form of icebergs, which were allowed to move about the Atlantic and slowly melt, producing a more realistic spreading of the direct release of freshwater over a much wider region, but at a slower rate [*Levine and Bigg*, 2008].

3. Results

3.1. The $\delta^{18}O_{G.\ bulloides}$ Gradients

[21] The core top gradient in stable oxygen isotope values of the planktonic foraminiferal species *Globigerina bulloides* ($\delta^{18}O_{G.\ bulloides}$) between 10°W and 3°E is similar to that predicted for calcium carbonate precipitated in equilibrium from surface water in early spring (Figure 5), the main season of *G. bulloides* growth in the region today [*Pujol*, 1980]. This suggests that the paleodata compilations presented in Figure 3 offer a useful representation of surface hydrographic conditions, revealing consistently heavier $\delta^{18}O_{G.\ bulloides}$ values in the Mediterranean than in the Atlantic throughout the last 30 Cal. ka BP (Calibrated kilo-years Before Present; hereafter referred to as ka). This W–E gradient in $\delta^{18}O_{G.\ bulloides}$ is exemplified by comparison of cores D13898 [*Rogerson et al.*, 2004] and MD95-2043 [*Cacho et al.*, 1999; *Sierro et al.*, 2005] (Figure 6). These cores respectively represent the Gulf of Cadiz and Alboran Sea, have similar and relatively high sampling resolution and also have a high degree of synchronicity in the age assignment of HS1 and HS2 making them the most easily comparable pair of records. Figure 6 shows a stable offset of about 0.7‰ during the early Holocene, 1.0–1.1‰ during the Younger Dryas and Bølling-Allerød, and about 1.8‰ during the LGM. During Heinrich Stadial 1, however, the isotope contrast between D13898 and MD95-2043 appears to have reduced to <0.5‰. This reduction is supported by the compilation of records shown in Figure 5. A smaller reduction in gradient is found during Heinrich Stadial 2 (Figure 5), although this is not so evident from comparison of D13898 and MD95-2043 alone (Figure 6). Linear regressions to the data from all cores (shown in Figure 5) indicate a core top west to east $\delta^{18}O_{G.\ bulloides}$ gradient of 0.129‰ degree^{-1}, which was increased to 0.258‰ degree^{-1} during the LGM. Heinrich Stadials 1 and 2 show west to east gradients that are much reduced

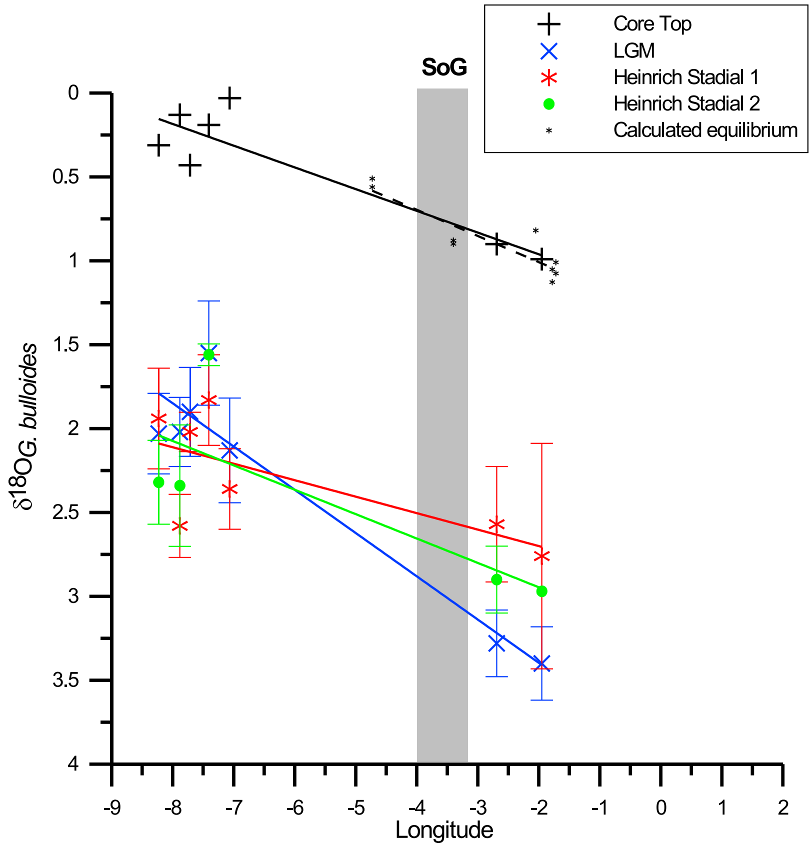

Figure 5. Compilation of $\delta^{18}O_{G.\ bulloides}$ data for core tops and mean values for HS1, HS2 and LGM (1 standard deviation shown as vertical error bars). Equilibrium values are shown as crosses, calculated from data from GISS sea-water stable isotope database [*Schmidt et al.*, 1999]. Calculations performed according to a standard paleotemperature equation [*Elderfield and Ganssen*, 2000] $\{\delta^{18}O_c = \delta^{18}O_w - 0.27 + [4.38 - (4.38^2 - 0.4(16.9 - SST)^{0.5})]/0.2\}$. Longitude given in °E, so that negative values indicate °W.

compared to the LGM of 0.098‰ degree^{-1} and 0.145‰ degree^{-1}, respectively (Figure 5).

3.2. SST Gradients

[22] Compilation of mean summer and winter gradients across the Strait of Gibraltar, including values from hydrographic data, is shown in Figure 7. It is encouraging to note that ANN values for core tops suggest a similar seasonal change in gradient as that seen in hydrographic data, even though the absolute values are somewhat different (Figure 5). However, before ~9 ka BP summer SST appears to have been higher in the Gulf of Cadiz (Figure 7), a reversal of the core top pattern that indicates a significant change in mean surface circulation conditions comparable to a change resulting from a reversal of the prevailing wind.

[23] During the LGM, comparison of the Atlantic and Mediterranean ANN-derived summer and winter SST records shows significantly higher SST in the Gulf of Cadiz than in the Alboran Sea, with differences of up to 7°C in summer and up to 5°C in winter (Figure 7). More detailed comparison based on D13898 and MD95-2043 (Figure 8) shows that this SST gradient between the Gulf of Cadiz and the Alboran Sea generally decreases at the end of the deglaciation, followed by a minor further reduction during the Holocene. Between 17.5 and 16 ka (Heinrich Stadial 1) the Atlantic-Mediterranean temperature difference is reduced by more than 3°C, with a complete collapse centered on 16.5 ka. No analogous collapse is seen at the time of Heinrich Stadial 2, when the maximum summer SST drop in the Gulf of Cadiz is only ~3°C (in M39029–7) leaving a significant offset from Mediterranean SST, which is largely unchanged during this time. However, the results for Heinrich Stadial 2 must be treated with some caution due to the low sampling resolutions of the records through that interval.

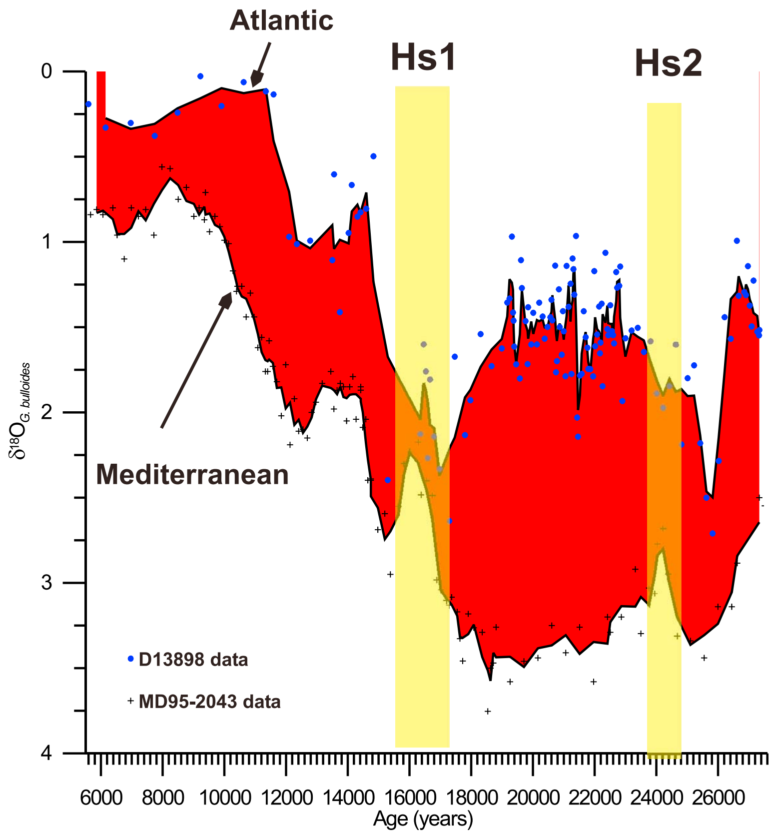

Figure 6. The $\delta^{18}O_{G.\ bulloides}$ records for cores D13898 (upper, blue points) and MD95-2043 (lower, black points). Lines represent 3-point moving average of data. Red area represents difference between cores ($\Delta^{18}O_{G.\ bulloides}$). Yellow vertical bars show duration of HS 1 and 2.

3.3. Modeling

3.3.1. One-Dimensional Modeling

[24] The primary impact of surface freshening related to AFEs is an increase in the net exchange (Q_{total}) across the Camarinal Sill. The magnitude of this impact is illustrated in Figure 9a. The relationship between Q_{total} and freshening is slightly nonlinear across the range of freshenings investigated ($\Delta Q_{total} \propto 0.13\Delta S_{atl} - 4.7 \times 10^{-3}\Delta S^2_{atl}$). The response of Q_{total} to sea level change is linear (Figure 9b), where $\Delta Q_{total} \propto 8.8 \times 10^{-3}\Delta$RSL. This behavior is consistent with the response reported for ΔQ_{atl} previously reported by [*Rohling and Bryden*, 1994], which is one half the size of the change in ΔQ_{total} as a result of the relationship between these two flux parameters ($\Delta Q_{total} = 2\Delta Q_{atl} - X_{med}$). X_{med} is the least constrained of the boundary conditions, but planktonic foraminiferal δ^{18}O evidence from the Mediterranean suggests that it varied only slightly during Heinrich Stadial 1 [*Bigg*, 1995; *Rohling*, 1999]. Nevertheless, exchange at Gibraltar is highly sensitive to the freshwater export flux, with higher fluxes driving enhanced exchange and vice versa. Mediterranean freshwater export flux (X_{med}) shows a nonlinear control on Q_{total} (Figure 9c), where $\Delta Q_{total} \propto 7.15\Delta X^{2/3}_{med}$.

3.3.2. GCM Modeling

[25] Figure 10 shows the response of the Gibraltar exchange to two North Atlantic iceberg release experiments, designed to simulate a Heinrich Event. With the onset of the Heinrich freshwater forcing (time 0), both simulations register an increase in Q_{atl}, with the iceberg simulation having a smaller effect because the freshwater is released over a wider region. Subsequent to the initial increase, both models show a decline in the scale of the anomaly back toward values typical of the control run, reflecting recirculation of low-density surface water within the Mediterranean. Significantly, an anomaly remains in both models until termination of the freshwater forcing after 500 years (Figure 10), with a non-smooth return over time toward the original exchange flux.

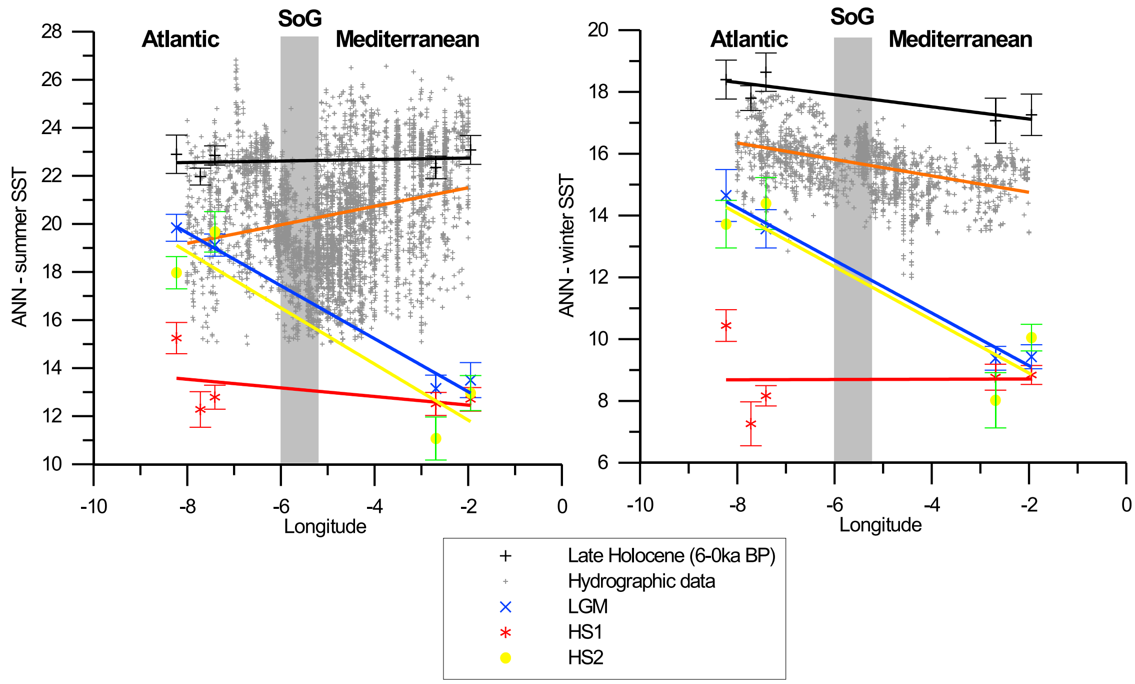

Figure 7. Compilation of ANN-SST data for cores for which planktonic foraminiferal assemblage data was available (1 standard deviation shown as vertical error bars. Summer (upper panel) and winter (lower panel) records are shown separately. Hydrographic data taken are for "summer" (JJA) and "winter" (JFM) from the *MEDATLAS*, 2002 data set. Orange line represents linear regression of MEDATLAS data, for comparison with regressions from core top data. Longitude given in °E, so that negative value indicate °W.

[26] Figure 11 shows the zonal velocity anomaly for the iceberg release experiment (hosing-control) just to the east of the Strait of Gibraltar, in the western Alboran Sea. Virtually no response is present below 500 m, apart from some slight increases in westward flux around 750 m. Virtually no response is present below 500 m, apart from some slight increases in westward flux around 750 m. The increase in Q_{total} therefore concerns predominantly the intermediate waters above that level (primarily Levantine Intermediate Water), compensated by an increase in Atlantic Inflow. This is consistent with previous suggestions based on multiproxy data reflecting bottom water renewal processes [*Rogerson et al.*, 2008].

4. Discussion

4.1. Thermal Gradient

[27] Two significant changes occur in the Strait of Gibraltar SST offset (ΔSST_{SoG}), namely, (1) an expansion of ΔSST_{SoG} in all seasons during the LGM and (2) a significant reduction of ΔSST_{SoG} during Heinrich Stadial 1.

4.1.1. Increased Surface Temperature Gradient During the LGM

[28] The strengthening (relative to the present) of the LGM ΔSST_{SoG} implies either increased vertical mixing in the Strait of Gibraltar or that cooling of some origin is being applied to surface water during its flow through the Gibraltar transect. The difference between the mean winter temperature offset between the Gulf of Cadiz and Alboran Sea (ΔwSST) is 4.7 ± 0.8°C (error for ΔwSST estimated by propagation of 1σ values for all Gulf of Cadiz and Alboran Sea LGM values via $\sigma\Delta wSST = \sqrt{\sigma wSST_{GoC}^2 + \sigma wSST_{Alb}^2}$), which is significantly greater than the late Holocene separation between wSST for the Gulf of Cadiz and MOW (3.6°C). Peak values in the separation between D13898 and MD95-2043 are ~7°C (Figure 8), double the present-day difference between Gulf of Cadiz winter SST and the temperature of MOW. It therefore seems unlikely that the observed glacial to interglacial changes in ΔSST_{SoG} can be explained by admixture of MOW to surface waters alone.

[29] Confirmation of the LGM strengthening in ΔSST_{SoG} is provided by the $\delta^{18}O_{G.\ bulloides}$ data,

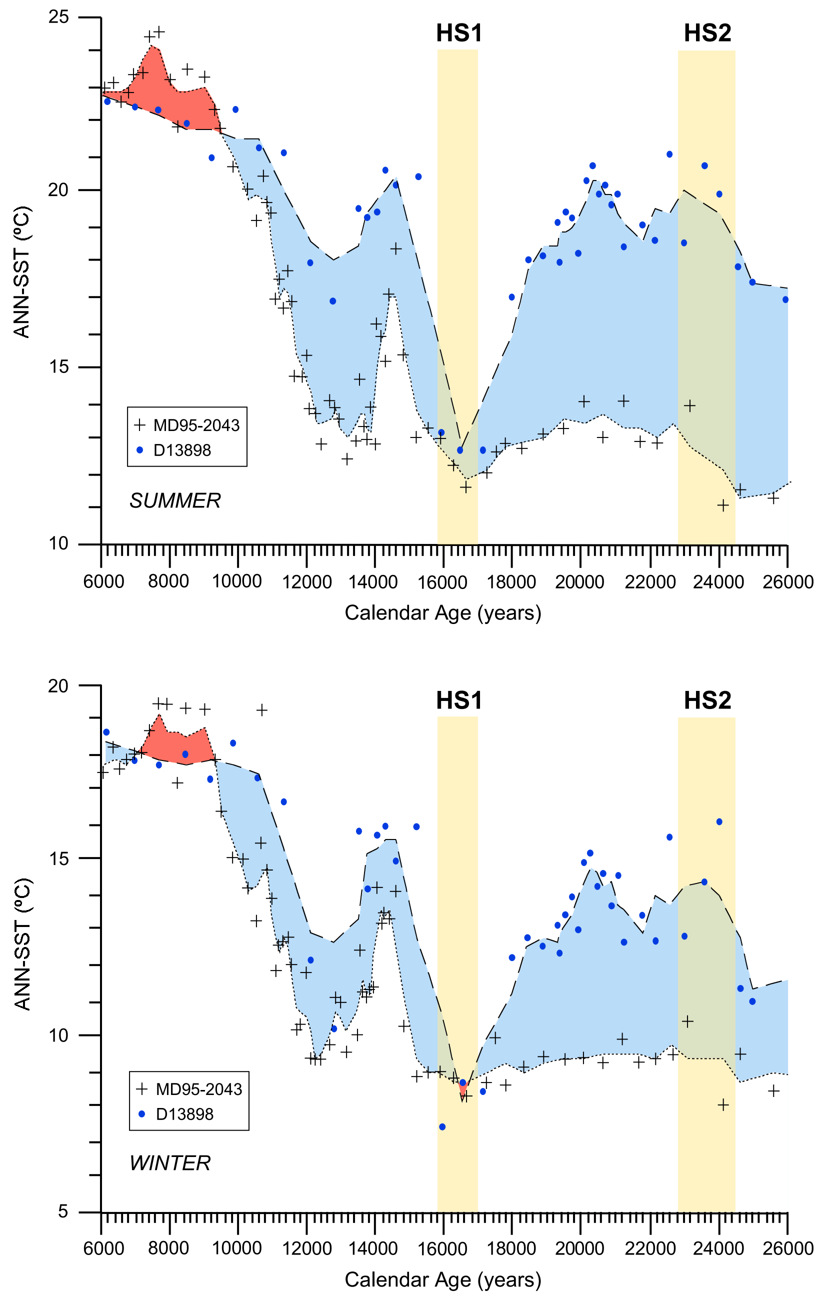

Figure 8. ANN-SST $_{bulloides}$ records for (top) D13898 (blue points) and (bottom) MD95-2043 (black points). Lines represent 3-point moving average of data. Colored area represents difference between cores (ΔSST), with red representing gradients analogous to today and blue representing periods of reversed gradient. Yellow vertical bars show duration of HS 1 and 2.

which shows an approximate doubling of the gradient (Figure 5). The $\delta^{18}O_{G.\ bulloides}$ data also offer some potential to further constrain the origin of the cold water, as admixture of MOW would cause a strong increase in the offset of $\delta^{18}O_{G.\ bulloides}$ from the Gulf of Cadiz and Alboran Sea, both due to the change in temperature of calcification and due to the admixture of isotopically heavy intermediate and deep waters to surface water in the Alboran Sea [*Schmidt et al.*, 1999]. Modern MOW is 0.5‰ heavier than regional surface waters, and the difference for the LGM likely was significantly higher due to the residence time effect [*Rohling*, 1999]. If the $\delta^{18}O_{water}$ offset increased approximately in proportion with ΔS_{Gib}, this would suggest a glacial offset of ~1‰. For the LGM, $\Delta\delta^{18}O_{G.\ bulloides}$ is 1.52 ± 0.42 ‰ and, assuming that $\delta^{18}O_{calcite}$ decreases with increasing temperature by 0.23‰ °C^{-1} [*O'Neil*

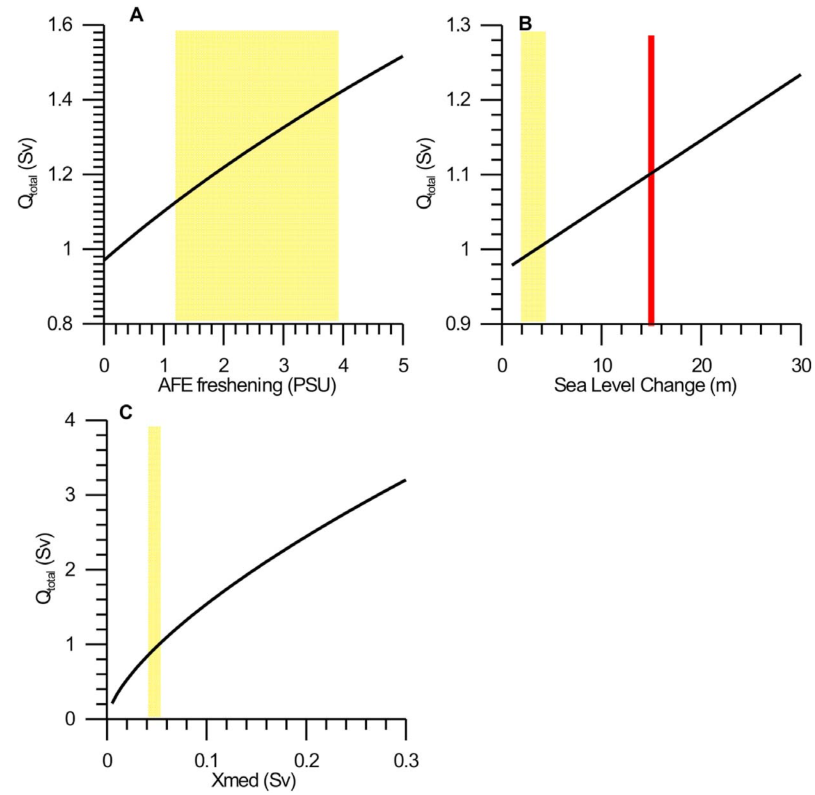

Figure 9. Output of 1-D modeling. (a) response of Q_{total} to changing salinity. The shaded area indicates the range of ΔS_{Atl} suggested by isotope excursions for AFE 1 (~1‰ in $\delta^{18}O_{water}$), assuming a range of $\delta^{18}O_{ice}$ values of −10 to −30‰. (b) Response of Q_{total} to changing sea level. Estimates for sea level rise as a result of Heinrich Events vary from 2 to 4 m [*Roche et al.*, 2004], indicated by the shaded area, to an estimated maximum value of 15 m [*Hemming*, 2004; *Rohling et al.*, 2004], indicated by the red line. (c) Response of Q_{total} to changing W_{Med}.

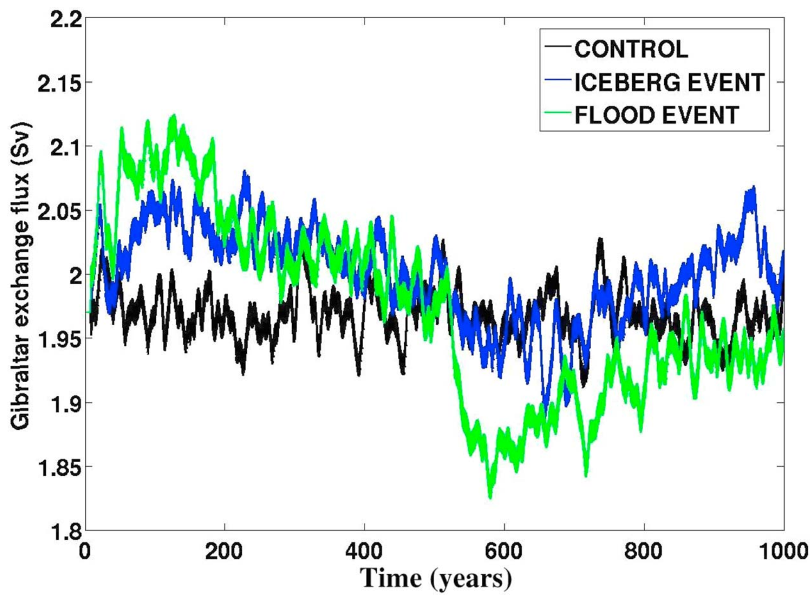

Figure 10. Response of Gibraltar exchange in two GCM simulations of Heinrich Event 1; green line represents Q_{atl} in a coupled model simulation of a Heinrich event as a freshwater release; blue line represents the same parameter in a simulation where the release was as icebergs. Time represents duration subsequent to the beginning of freshwater/ iceberg "hosing," which begins at "time 0."

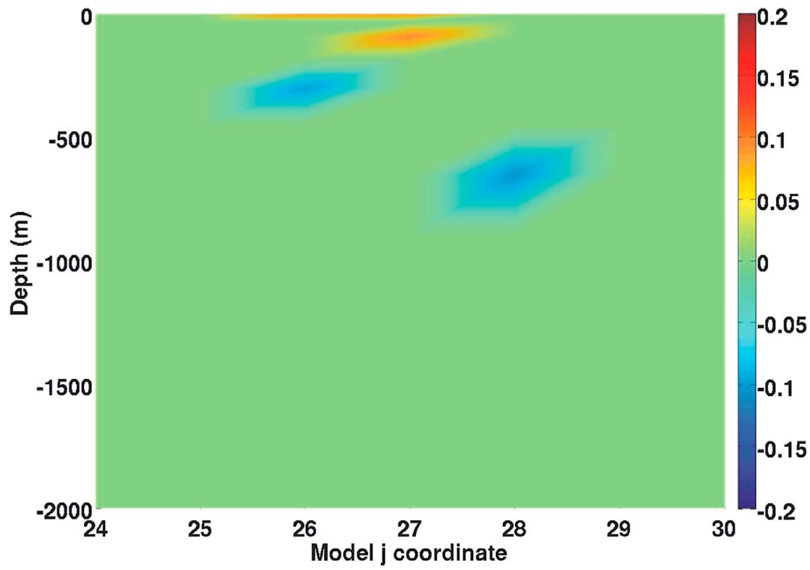

Figure 11. Zonal velocity anomaly (Heinrich Event - Control) with depth for a meridional section across the western Alboran Sea in the iceberg release simulation experiment shown as the blue line in Figure 10. The color scale is in cm/s. North Africa is to the left and southern Iberia is to the right. There is only weak flow below 500 m, apart from some westward flow toward the northern end of the Strait of Gibraltar. Surface inflow and deeper outflow are seen in the upper few hundred meters. Note the horizontal scale is in model grid points because of the rapidly changing grid length in this region [*Peltier*, 1994; *Wadley and Bigg*, 1999].

et al., 1969], this suggests that the $\delta^{18}O_{water}$ difference between Gulf of Cadiz and Alboran Seawater was in the region of 0.44‰. This indicates that the proportion of upwelled MOW in the surface waters of the Alboran Sea was similar to today (40–50%). However, propagating the standard deviations from the raw data gives a very high 1σ range for this estimate (±0.47‰) so it is not possible to make this case unambiguously.

[30] Changes in the hydrographic structure on both sides of Gibraltar have been previously reported for the LGM: to the west the Azores Front is argued to have penetrated into the Gulf of Cadiz [*Rogerson et al.*, 2004], and to the east the Alboran Gyres are believed to have been inactive before about 8 ka [*Rohling et al.*, 1995]. Incorporation into the Gibraltar inflow of cold surface water transported along the northern shelf of the Gulf of Cadiz would effectively place the Gulf of Cadiz and Alboran Sea locations on opposing sides of the Azores Front, which represents a ~4°C transition [*Gould*, 1985]. Incursion of cold surface water from the Gulf of Lions transported down the southern margin of Iberia would similarly provide cooling without significant increase of $\delta^{18}O_{water}$, with strong LGM cooling of the northwest Mediterranean magnifying this influence [*Hayes et al.*, 2005; *Kuhlemann et al.*, 2008]. Indeed, the concept of flow of cold water down the east Iberian margin during the LGM is given implicit support by the reconstructions of *Hayes et al.* [2005, Figure 9b] and also in those of *Kuhlemann et al.* [2008], which both show a strong temperature anomaly in this area. Notably, the strongest temperature anomaly in the *Hayes et al.* [2005] reconstruction is during the summer, when we find ΔSST_{Gib} to be reversed relative to today. Despite the uncertainty of the large propagated error in $\delta^{18}O_{water}$, we therefore argue that the glacial to interglacial changes in gradient most likely represent a significant reorganization of regional surface water circulation to a state not reported in modern data sets [*Folkard et al.*, 1997], with the collapse of the Alboran gyres allowing incursion of surface water from the Gulf of Lions transported southward due to enhanced atmospheric flow and reduced momentum in the Alboran surface layer caused by the reduced inflow of Atlantic water [*Rogerson et al.*, 2005; *Rohling and Bryden*, 1994].

4.1.2. Reduction in Gradients During Heinrich Stadials

[31] During Heinrich Stadial 1, both the summer and winter SST and $\delta^{18}O_{G.\ bulloides}$ gradients were considerably reduced (Figure 7). The strong and consistent cooling across the Strait of Gibraltar

found during the LGM therefore does not appear to have occurred during Heinrich Stadial 1, indicating a reduction in mixing during transport through the Strait. However, mean $\Delta\delta^{18}O_{G.\ bulloides}$ for Heinrich Stadial 1 is 0.59 ± 0.61 ‰, which in the absence of strong SST gradients would imply slightly heavier $\delta^{18}O_{water}$ to the east of Gibraltar, and consequently the maintenance of some upwelling within the strait. In combination, these observations imply that Gulf of Cadiz surface water was at a similar temperature to MOW. The timing of this period is consistent with an observed collapse of the gradient between one of the cores in this study (D13898) and MD95-2042 on the Portuguese margin [*Rogerson et al.*, 2004], and it seems likely that surface water gradients were generally small from offshore Lisbon to the eastern Alboran Sea. The inferred simultaneous collapse/withdrawal of the Azores Front and reduction in mixing within the Strait of Gibraltar indicate a significant enhancement of surface water stratification, as would be expected during admixture of a large flux of freshwater from iceberg melting.

[32] During Heinrich Stadial 2, the response in the $\delta^{18}O_{G.\ bulloides}$ records was smaller than during Heinrich Stadial 1 (Figure 5) and very little SST change is observed (Figure 7). We infer that the response of the Gibraltar exchange to this event was small relative to Heinrich Stadial 1. In this context, it should be noted that Heinrich Stadial 2, unlike Heinrich Stadial 1, also failed to cause a collapse in the surface hydrographic gradients between the Gulf of Cadiz and the Portuguese margin and so does not appear to have strongly affected the Azores Front [*Rogerson et al.*, 2004]. It should be noted, however, that the amount of data available for Heinrich Stadial 2 is far less than for Stadial 1, the proof of synchronicity is less secure and it therefore remains possible that this apparently lower magnitude impact is an artifact of sampling.

4.2. Synthesis of Modeling and Empirical Evidence

[33] The surface gradients at Gibraltar appear to be approximately comparable for Heinrich Stadial 1 and the early Holocene, in spite of significant climatic differences between these two periods. The reason for this similarity must therefore reflect a similarity in the level of control over the region exercised by the Gibraltar Exchange at these times. Both 1-Dimensional and GCM modeling indicate that the response of the Gibraltar Exchange to a Heinrich Event in the Atlantic would be for the Gibraltar exchange flux (Q_{total}) to increase (Figures 9 and 10). Consequently, during both the Holocene and Heinrich Stadial 1, Q_{total} was significantly higher than during the LGM, making the underlying regional hydrographic structure similar during these two times. The empirical and modeling evidence therefore provide a coherent picture in which enhanced Gibraltar exchange causes simplification of regional surface circulation patterns, effectively flattening regional surface property gradients.

4.3. Temporal and Spatial Structure of Enhanced Gibraltar Exchange During Heinrich Stadial 1

[34] The methods presented in this study show a high level of consistency in their reconstruction of hydrographic changes during Heinrich Event 1, and add confidence to inferences of freshened surface water incursion into the westernmost Mediterranean reported in previous literature. A subtle but potentially important difference lies in the fact that, whereas in this study AFE's are apparently sustained throughout Heinrich Events, the low $\delta^{18}O_{water}$ pulses reported by *Sierro et al.* [2005] are often of extremely short duration (a few centuries) and positioned toward the end of each Heinrich Stadial period [see *Sierro et al.*, 2005, Figure 3]. Given the control of the system detailed in Figure 9, negligible rates of sea level rise during Heinrich Stadial 1 [*Hanebuth et al.*, 2000; *Peltier and Fairbanks*, 2006] and the lack of evidence for enhanced freshwater export flux in marine $\delta^{18}O$ compilations [*Rohling*, 1999], the inference must be that surface water in the Gulf of Cadiz was freshened throughout the Heinrich Stadial 1 period. Freshening in the Gulf of Cadiz therefore did not only occur as discrete, short duration peaks of iceberg melting, but was sustained throughout Heinrich Stadial periods. This continuous meltwater input requires a considerable flux of icebergs/meltwater into the southwest Iberian margin region, as has been suggested from GCM experiments [*Levine and Bigg*, 2008].

[35] The GCM results provide insight into the vertical structure of the anomalous flow within the Strait of Gibraltar induced by Atlantic freshening, showing virtually no change in flow at depth within the westernmost Mediterranean but strong velocity anomalies in the surface and intermediate layers. Consequently, enhanced circulation within the western Mediterranean seems to be restricted to the upper 750 m. This observation is important, as it may partially decouple the Gibraltar exchange changes described in this study from changes in bottom ventilation in the Alboran Sea described elsewhere

[*Cacho et al.*, 2000, 2006; *Frigola et al.*, 2007; *Jiménez-Espejo et al.*, 2007; *Sánchez-Goñi et al.*, 2002; *Sierro et al.*, 2005]. Transmission of ventilation changes to the deep western Mediterranean basin therefore must have occurred via the Bernoulli suction mechanism outlined by *Rogerson et al.* [2008].

4.4. Consequences of an Enhanced Gibraltar Exchange

[36] For the Mediterranean, the consequences of enhanced exchange are reduced residence time and slightly reduced mean salinity. Neither of these impacts is easily resolvable in the proxy record beyond the immediate vicinity of Gibraltar [*Rogerson et al.*, 2008]. However, from an Atlantic perspective, enhanced Gibraltar exchange would result in an increased flux of surface buoyancy out of the Atlantic and an increased flux and decreased salinity (and therefore increased buoyancy) of MOW injection into intermediate depths. Increased flux is reflected in peaks in MOW activity throughout the Gulf of Cadiz during Heinrich Stadials [*Llave et al.*, 2006; *Toucanne et al.*, 2007; *Voelker et al.*, 2006]. Enhanced flow at relatively shallow depths [*Llave et al.*, 2006; *Toucanne et al.*, 2007] also provides evidence for reduced-density related shoaling of the MOW plume [*Rogerson et al.*, 2005]. A larger, shallower MOW plume within the North Atlantic would have consequences for recovery of Atlantic meridional overturning subsequent to freshening related to Heinrich Event iceberg meltwater [*McManus et al.*, 2004; *Sarnthein et al.*, 1994; *Schönfeld and Zahn*, 2000], as the northward transport of intermediate depth salt would be enhanced and the probability of mixing this salt to the surface would also be enhanced.

4.5. Further Significance of the Exchange Enhancement Process

[37] *Rogerson et al.* [2006a] reported enhanced MOW flow at both Termination 1a (~15.5 ka) and 1b (~11.5 ka). At the time of publishing this earlier study, no explanation for this abrupt behavior was identified. However, strong analogies can be drawn with MOW flow conditions during Heinrich Events [*Llave et al.*, 2006; *Voelker et al.*, 2006], implicating a similar forcing. Rapid sea level rises, which in the case of Termination 1a has similar timing to a pulse of meltwater into the North Atlantic [*Fairbanks*, 1989; *Peltier and Fairbanks*, 2006; *Stanford et al.*, 2006], coincide with these periods of MOW enhancement. Linkage between Gibraltar exchange and Atlantic sea level/freshwater forcing therefore provides a coherent explanation for the deglacial MOW variability documented by *Rogerson et al.* [2006a] and *Schönfeld and Zahn* [2000], as well as the glacial variability reported by other authors [*Llave et al.*, 2006; *Toucanne et al.*, 2007; *Voelker et al.*, 2006].

5. Conclusions

[38] Increased trans-Gibraltar SST and $\delta^{18}O_{G.\ bulloides}$ gradients during the LGM indicates a circulation not analogous to the present. The $\delta^{18}O_{G.\ bulloides}$ and SST data combined indicate increased mixing with cold water during eastward transport of surface water through the Strait of Gibraltar during the LGM compared to today. The size of the LGM SST offset between the Gulf of Cadiz and Alboran Sea makes it unlikely that all of this additional cooling is due to increased upwelling of MOW. Admixture of northern surface waters transported from the Portuguese margin and the Gulf of Lions are proposed as alternatives, with the latter preferred due to published evidence of southward extension of cold, surface water in this direction [*Hayes et al.*, 2005; *Kuhlemann et al.*, 2008]. Removal of temperature effects from $\delta^{18}O_{G.\ bulloides}$ is ambiguous due to large propagated errors, but provides some support for this concept. Transport of northern surface waters down the eastern margin of Iberia reflects decreased momentum within the surface layer of the Alboran Sea, related to the decreased flow of inflowing Atlantic water.

[39] Significant reductions in the sea surface temperature gradient and planktic foraminiferal $\delta^{18}O_{G.\ bulloides}$ gradient across the Strait of Gibraltar during Heinrich Stadial 1 indicates a major change in surface circulation patterns. Despite significant climatic differences, the Heinrich Stadial 1 and early Holocene gradients are similar, suggesting similar circulation patterns and thus high fluxes of inflowing Atlantic water. 1-D and GCM modeling provides an explanation for this, namely that during both periods the Gibraltar exchange was significantly higher than during the LGM. The changes are not so apparent during Heinrich Stadial 2, suggesting that the impact of this event on the Gibraltar exchange was smaller. However, this event is not as well resolved as Heinrich Stadial 1 in our data set, so some doubt over this observation remains.

[40] Enhanced Gibraltar exchange is consistent with changes in ocean bottom conditions in the Alboran Sea and changes in the activity of the MOW.

Furthermore, changes in North Atlantic water masses during the last deglacial provide an explanation for the repeated intensifications of the MOW reported by previous authors [*Rogerson et al.*, 2006a]. Consequently, when surface water in the North Atlantic freshens, reducing the rate of Meridional Overturning, the exchange at Gibraltar is actually enhanced, increasing the loss of buoyancy via cooling and evaporation within the Mediterranean basin. This observation could be critical in understanding how Atlantic Meridional Circulation restarts after periods of stagnation.

Acknowledgments

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