The climate influence on the mid-depth Northeast Atlantic gyres viewed by cold-water corals

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[1] The neodymium (Nd) isotopic composition (expressed in epsilon units, εNd) of reef framework-forming cold-water corals provides unique measures of water mass provenance and mixing within the Northeast Atlantic today and in the past. A reconstruction of near thermocline water εNd from cold-water corals of the Gulf of Cádiz and Porcupine Seabight spanning over the past 300,000 years, now revealed that climate cooling during Marine Isotope Stages (MIS) 7.2 and MIS 8/9 led to a retraction of the mid-depth Subpolar Gyre (mSPG) to the west. Conversely, Northern Hemisphere warming and increasing fresh water fluxes to the northwest (Labrador Sea) favor a stronger eastward extension of the mSPG blocking the northward flow of temperate Atlantic water as observed during the early MIS 1 and the early stage MIS 5.5. These changes are likely the result of large-scale south-north displacement of the westerlies similar to present-day observations that the North Atlantic Oscillation (NAO) is linked with mid-depth ocean circulation. Based on these observations, we hypothesize that further climate warming will also strengthen the mSPG leading to a salt and temperature decrease in the Northeast Atlantic whereas salinity and temperature will increase in the temperate Atlantic. However, the amplitude of such changes on North Atlantic overturning remains to be tested.

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1. Introduction

1.1. Mid-depth North Atlantic Circulation

[2] The present day mid-depth ocean circulation patterns in the Northeast Atlantic are characterized by two major gyres and an East Atlantic boundary under current [*Bower et al.*, 2002; *Hátún et al.*, 2005; *Lozier and Stewart*, 2008]. The cyclonic mid-depth Subpolar Gyre (mSPG; Figure 1a) re-circulates water within the Northwest Atlantic throughout the Labrador and Iceland basins and mixes Labrador slope waters into the northeastward spreading mid-depth waters. The anticyclonic mid-depth Subtropical Gyre (mSTG; Figure 1a) re-circulates water throughout the temperate Atlantic. To the east, Mediterranean Sea Water (MSW), a mixture of Mediterranean Outflow Water (MOW), Eastern North Atlantic Central Water (ENACW) and East Antarctic Intermediate Water (EAAIW), propagates to the north as boundary undercurrent (Figure 1a) [*McCartney and Mauritzen*, 2001; *Lozier and Stewart*, 2008; *Khelifi et al.*, 2009; *Copard et al.*, 2011]. However, there is an active debate on whether MSW may enter Rockall Trough to contribute directly to the Nordic inflow and feed high salinity water also into the mSPG [*Rahmstorf*, 1998; *McCartney and Mauritzen*, 2001; *Bower et al.*, 2002; *Dickson et al.*, 2002; *Hátún et al.*, 2005; *Lozier and Stewart*, 2008], but its effect on the North Atlantic overturning circulation and therefore on the Northern Hemisphere climate is not well constrained [*Rahmstorf*, 1998].

[3] Cold-water corals, being widespread ecosystem engineers in water depths between 200–2000 m along the Northeast Atlantic margins [*Davies et al.*, 2008], have been shown to act as useful archives to reconstruct rapid changes in ocean chemistry and water mass dynamic [*van de Flierdt et al.*, 2010; *Copard et al.*, 2010, 2011]. Their aragonitic skeleton can be absolutely dated by means of mass spectrometric U-Th dating [*Cheng et al.*, 2000; *Douville et al.*, 2010]. It has recently been shown that the neodymium (Nd) isotopic compositions - expressed here as $\varepsilon\text{Nd} = ([(^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}}/(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}] - 1) \times 10000$ (CHUR: Chrondritic Uniform Reservoir [*Jacobsen and Wasserburg*, 1980]) - of living and Holocene cold-water corals from the Gibraltar Strait to the Norwegian Sea seem to faithfully trace water mass provenance and mixing of Northeast Atlantic mid-depth water masses [*Colin et al.*, 2010; *Copard et al.*, 2010, 2011]. This is because cold-water coral skeletons ones carefully cleaned allow retrieving the isotopic composition of water masses and any remaining contamination (residual Fe/Mn coatings) will most likely carry the local seawater signature [*van de Flierdt et al.*, 2010; *Copard et al.*, 2010, 2011]. Variations of the isotopic composition of cold-water corals through time therefore most likely reflect processes altering the sea water isotopic compositions of water masses bathing the corals while than are actively growing their aragonite skeleton. In the mid-depth ocean, the only way to alter the initial Nd isotopic composition of water masses is to add Nd with a different isotopic composition through riverine and eolian inputs and boundary exchange or by mixing isotopically different water masses [e.g., *Lacan and Jeandel*, 2005]. However, away from active continental margins and

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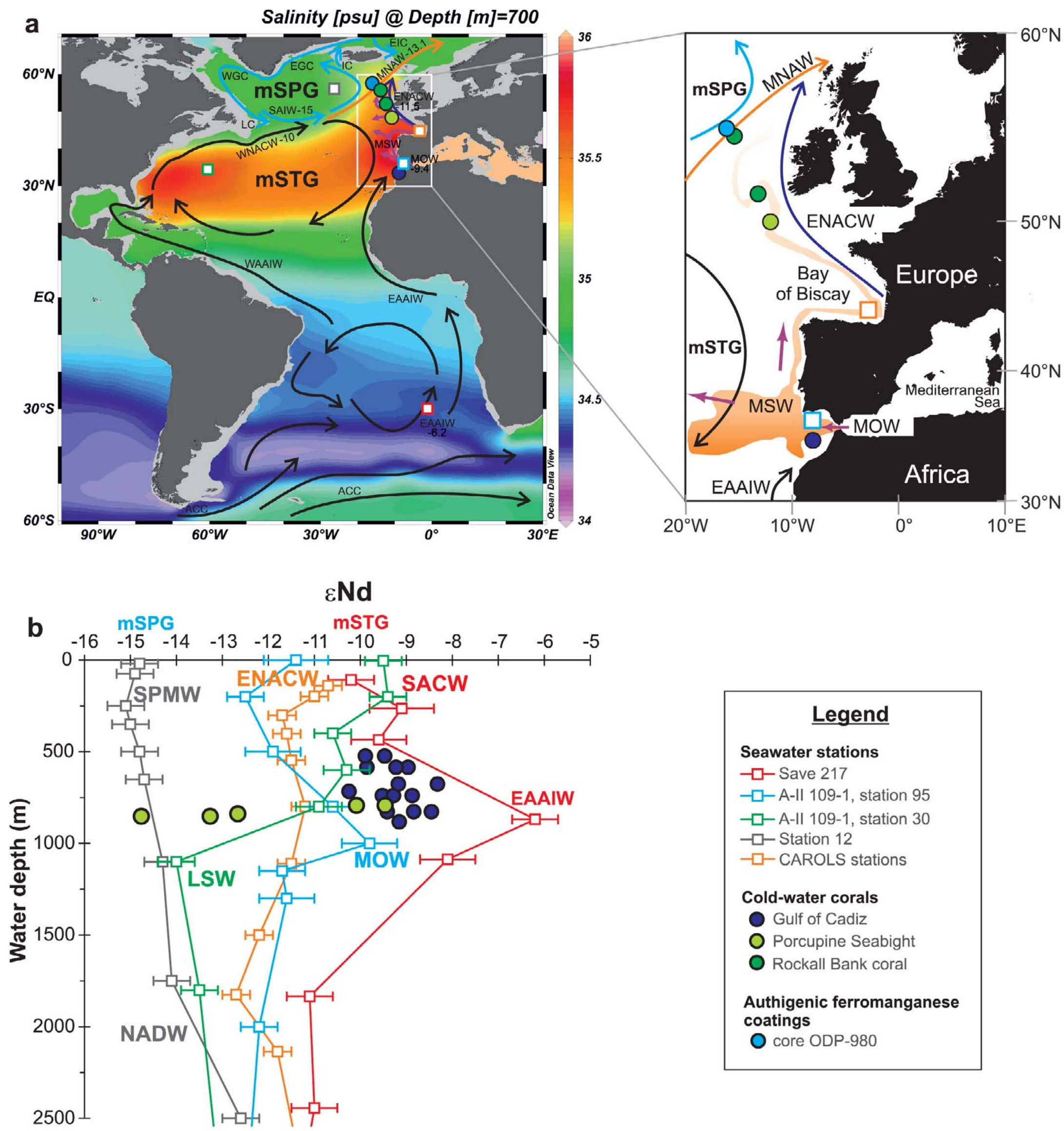

Figure 1. (a) Salinity contour map of the Atlantic Ocean at 700 m water depth (Ocean Data View; WOA 2009 dataset) and location of cold-water corals and seawaters stations discussed in this study. The main surface and intermediate-water masses of the Atlantic Ocean are also represented. (b) εNd versus water depth (m) for cold-water corals investigated in this study. εNd profiles from 5 representative seawater stations are also represented for comparison. A-II 109-1, station 95 [*Piepgras and Wasserburg*, 1983]; A-II 109-1, station 30 [*Piepgras and Wasserburg*, 1987]; Save 217 [*Jeandel*, 1993]; CAROLS stations [*Copard et al.*, 2011]; GINS cruise, station 12 [*Lacan and Jeandel*, 2004]; core ODP-980 [*Crocket et al.*, 2011]; Rockall Bank cold-water corals [*Colin et al.*, 2010]. Water masses are LC: Labrador Current, SAIW: Sub-Arctic Intermediate Water, WGC: Western Greenland Current; EGC: East Greenland Current, IC: Irminger Current, EIC: East Icelandic Current, MNAW: Modified North Atlantic Water, WNACW: Western North Atlantic Central Water, ENACW: Eastern North Atlantic Central Water, MOW: Mediterranean Outflow Water, MSW: Mediterranean Sea Water, EAAIW: Eastern Antarctic Intermediate Water, WAAIW: Western Antarctic Intermediate Water, ACC: Antarctic Circumpolar Current, SPMW: Subpolar Mode Water, LSW: Labrador Sea Waters, NADW: North Atlantic Deep Water, SACW: South Atlantic Central Water, mSPG: mid-depth Subpolar Gyre, mSTG: mid-depth Subtropical Gyre.

on short time scales during which the corals precipitate their skeleton (<20–100 years), εNd can be considered a quasi-conservative tracer in the ocean given its long residence time of ~1000 yrs [*Tachikawa et al.*, 2003]. Hence, εNd records of cold-water corals provide a way to reconstruct changes in water mass dynamic through time related to climate change.

1.2. Seawater εNd Variations in the Northeast Atlantic

[4] Along the Northeast Atlantic marginal seas mid-depth water masses from subpolar and subtropical regions compete with each other, steering variability of the salt and temperature balance throughout the basins. Those competing water masses carry significant differences in terms of εNd signature (Figure 1a). The mSPG water is characterized

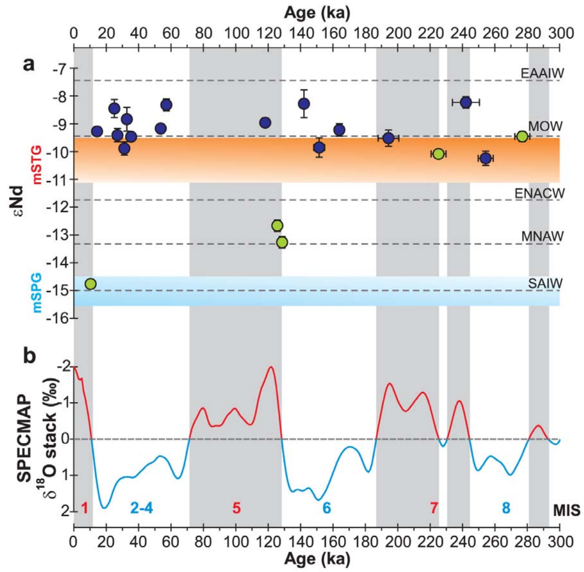

Figure 2. (a) Variations in εNd versus age (ka) of cold-water corals from the Porcupine Seabight and Gulf of Cádiz. Mean εNd values of intermediate water masses of the Northeast Atlantic are also reported (gray dashed arrowed lines). EAAIW: Eastern Antarctic Intermediate Water [*Jeandel*, 1993]; MOW: Mediterranean Outflow Water [*Tachikawa et al.*, 2004]; ENACW, Eastern North Atlantic Central Water [*Rickli et al.*, 2009; *Copard et al.*, 2011]; MNAW: Modified North Atlantic Water [*Copard et al.*, 2010]; MSW: Mediterranean Sea Water [*Copard et al.*, 2010, 2011]; SAIW: Sub-Arctic Intermediate Water [*Lacan and Jeandel*, 2004]. mSPG: mid-depth Subpolar Gyre, mSTG: mid-depth Subtropical Gyre. (b) Marine Isotope Stages (MIS) are indicated by blue (glacial) and red (interglacial) line based on SPECMAP δ^{18}O stack [*Imbrie et al.*, 1989].

today by low εNd with mean values ranging between −15 and −13.5 along the gyre boundaries [*Lacan and Jeandel*, 2004]. Conversely, mSTG waters are characterized by higher εNd values of −10.2 to −11.7 resulting from the mixing of MOW (εNd −9.4 ± 0.5 [*Tachikawa et al.*, 2004]) and ENACW (εNd −11.7 ± 0.3 [*Rickli et al.*, 2009; *Copard et al.*, 2011]) with the fresher mSTG water (εNd ~ −10.4 [*Piepgras and Wasserburg*, 1987]) originating in the temperate West Atlantic (Figure 1a). It needs to be emphasized that along the northward route of MSW its isotopic composition evolves today through successive dilution with ENACW to values of −11.5 within the Bay of Biscay [*Rickli et al.*, 2009; *Copard et al.*, 2011]. Thus, at present, mSTG, MSW, and ENACW can not be distinguished by its Nd isotopic composition north off Portugal.

[5] Today, mid-depth waters entering Rockall Trough to the south are composed of εNd values of −13.8 ± 0.3 and further east in the Porcupine Seabight, modern cold-water corals suggest ambient seawater εNd values of around −12.3 ± 0.3 [*Copard et al.*, 2010]. The influence of non radiogenic Nd advected from the mSPG is well attested in agreement with recent hydrographic observations [*Bower et al.*, 2002; *Lozier and Stewart*, 2008; *Copard et al.*, 2010]. Thus, a large contrast between northern and southern water masses ($\Delta\varepsilon$Nd ~2) exists today along the eastern basin boundary indicating the competition of northeastern and southern mid-depth water masses.

[6] Likewise, large variations of the seawater εNd in Rockall Trough and Porcupine Seabight have been observed over the course of the Holocene [*Colin et al.*, 2010] with values ranging between −11.8 to −15 (Figure 3a), indicating significantly lower and higher proportions of mSPG water compared to modern observations (εNd −12.3 to −13.8). Those variations were interpreted as significant changes of the mass balance between mSPG and mSTG (the latter including MSW and ENACW), supposing that mSTG and mSPG end-member εNd values remained constant. In addition, *Colin et al.* [2010] suggested that the eastward extension of mSPG water depends mainly on the position and strength of westerly winds. However, the Holocene warm period presents solely minor climate change in terms of cooling and warming of the northern Hemisphere driven by changes in the wind fields and in particular the early Holocene is affected by large fresh water fluxes to the Labrador Sea from residual ice sheet melting.

[7] Here we present new Nd-isotopic measurements on fossil cold-water corals from two sites along the Northeast Atlantic margin, the Porcupine Seabight (51°N) and the Gulf of Cádiz (35°N) (Figures 1b, 2a, and 3a), that have been achieved through an improved analytical procedure for Nd-oxyde isotope measurements as outlined in the

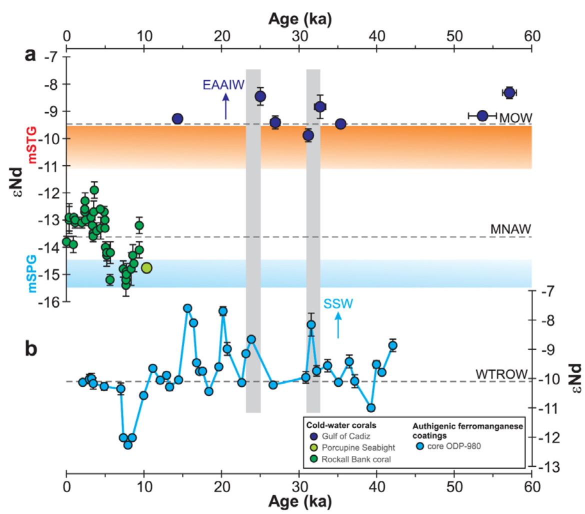

Figure 3. Comparison of (a) εNd records of the cold-water corals from the Porcupine Seabight (this study), Gulf of Cádiz (this study), and Rockall Bank (data from *Colin et al.* [2010]) with (b) εNd record derived from authigenic ferromanganese coatings of the core ODP-980 from the Rockall Bank (data from *Crocket et al.* [2011]). Mean εNd values of intermediate and bottom water masses of the Northeast Atlantic are also reported (gray dashed arrowed lines). EAAIW: Eastern Antarctic Intermediate Water [*Jeandel*, 1993]; MOW: Mediterranean Outflow Water [*Tachikawa et al.*, 2004]; MNAW: Modified North Atlantic Water [*Copard et al.*, 2010]; WTROW: Wyville-Thomson Ridge Overflow Water [*Crocket et al.*, 2011]; SSW: Southern Source Water (present in the trough at depths >3000 m; εNd ~7 [*Crocket et al.*, 2011]); mSPG: mid-depth Subpolar Gyre, mSTG: mid-depth Subtropical Gyre.

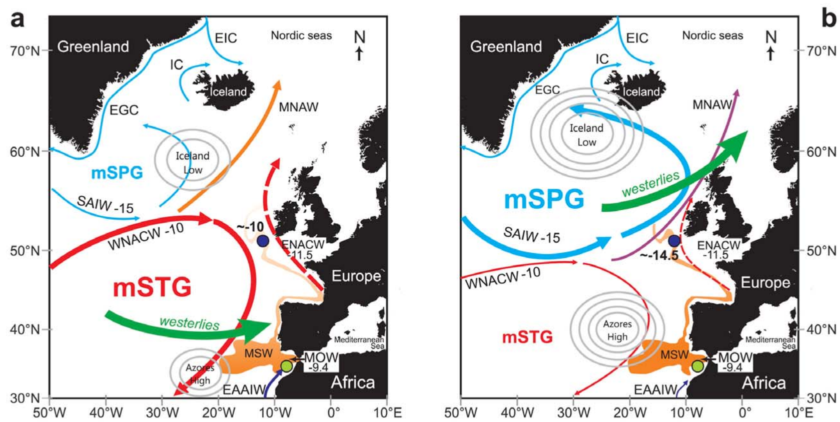

Figure 4. Generalized schematic representations of the dynamic of mid-depth circulation in the Northeast Atlantic during (a) MIS 7.4 and 8/9 and (b) MIS 1 and 5.5. Prevailing westerlies regimes (green arrows) are interpreted after *Hurrell and Dickson* [2004] and *Chen et al.* [2010]). The main surface and intermediate-water masses of the North Atlantic with their respective εNd are also represented (εNd data from *Copard et al.* [2010]). Labels for the water masses are as in Figure 1.

auxiliary material.[1] εNd values were obtained from U-series dated fossil cold-water coral fragments retrieved from coral-bearing sediment cores and from TV-guided grab samplers with coral ages spanning from today to the past 300,000 years [*Eisele et al.*, 2008; *Wienberg et al.*, 2009, 2010; *Frank et al.*, 2011].

2. Results: εNd of Cold-Water Corals

[8] During the past 260,000 years, coral εNd in the Gulf of Cádiz varies between −8 and −10 (Figures 1b and 2a) similar to surrounding modern seawater εNd from the mSTG and MOW [*Piepgras and Wasserburg*, 1983, 1987; *Copard et al.*, 2011]. In contrast, within the Porcupine Seabight, coral εNd values show large variations, from −15 at the start of the Marine Isotope Stage (MIS) 1 to as high as −9 during the early MIS 8 (Figure 2a). During the climate warm stages MIS 1 (Holocene) and MIS 5.5 (Last Interglacial) coral εNd reveal a large contrast between southern and northern water masses ($\Delta\varepsilon$Nd ~2 to 4), similar to the present-day water mass isotopic compositions (Figure 2a). Conversely, during times of more extensive Northern Hemisphere ice cover (MIS 7.4 and 8/9) corals yield significantly higher εNd values (−9.5 to −10.5), which are close to the mean value of fossil cold-water corals from the Gulf of Cádiz and more radiogenic compared to modern observations (εNd ~−13.8 [*Copard et al.*, 2010]) (Figures 1b and 2a). These coral εNd variations in the Porcupine Seabight reveal strong changes of the provenance of water bathing the coral reefs within Porcupine Seabight and imply a higher proportion of mid-depth waters originating from the mSTG/MSW compared to the present-day and the values obtained for MIS 1 and MIS 5.5 (Figures 1b and 2a).

3. Discussion: Variability of the Mid-depth Northeast Atlantic Gyres

[9] The observed variations in the mid-depth Atlantic gyres during periods of the climate cooling (MIS 7.4 and 8/9) and warming (MIS 1 and 5.5) may be related to latitudinal changes of the mid-latitude westerly winds over the North Atlantic [e.g., *Toggweiler et al.*, 2006; *Bakke et al.*, 2008; *Chen et al.*, 2010; *Colin et al.*, 2010], which in turn have a direct influence on the strength and shape of mSPG circulation [e.g., *Lozier and Stewart*, 2008; *Colin et al.*, 2010].

[10] Indeed, during times of more extensive Northern Hemisphere ice cover enhanced westerlies occurred most likely at more southern locations between 38–45°N [e.g., *Calvo et al.*, 2001; *Helmke and Bauch*, 2003; *Bakke et al.*, 2008; *Eynaud et al.*, 2009]. This situation (Figure 4a), thus must have led to a contraction of the mSPG, allowing a stronger northward advection of temperate Atlantic mid-depth water masses (mSTG/MSW) into Porcupine Seabight. This configuration is thought to be responsible for the more radiogenic εNd values (−9.5 to −10.5; Figures 1b and 2a) observed in the mid-depth water mass of the Porcupine Seabight during rather cold episodes of the MIS 7.4 and 8/9. Note that the MIS 7.4 and 8/9 represent colder climate periods compared to the MIS 1 and MIS 5.5, but strongly warmer compared to glacial climate periods (Figure 2b). Thus, the full glacial mid-depth circulation remains yet unknown. Moreover, similar to modern climate observations - such as the North Atlantic Oscillation or NAO [*Hurrell and Dickson*, 2004] - a decrease in the pressure gradient between the Azores High and the Iceland Low can also induce the southern migration of the westerlies at those times. Alternatively, a reduction and shoaling of North Atlantic deep water formation during Northern Hemisphere cooling does favor enhanced Antarctic Intermediate Water propagation to the north (Figure 3), potentially filling most of the Atlantic basin at mid-depth during glacial conditions [e.g., *Pahnke et al.*, 2008; *Crocket et al.*, 2011; *Gutjahr and Lippold*, 2011]. In such a scenario, the northward contribution of EAAIW may become significantly more radiogenic during periods of Northern Hemisphere cooling leading to increased εNd signature along the Northeast Atlantic margin. However, in such a scenario one would expect that the Nd isotopic composition of water masses in the Gulf of Cádiz would also become more radiogenic. But this does not seem the case as even during full glacial conditions values remain in a narrow range between −8 and −10 (Figure 3).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048733.

Unfortunately, investigated corals are not coeval and thus we can not exclude changes in the isotopic composition of water masses in the Gulf of Cádiz. But given the highest glacial values as observed so far (~−8.5) the north-south isotopic gradient remains small (<2 εNd units) compared to present-day and during climate warm stages (3–6 εNd units).

[11] Finally, we may simply assume that the eastward extension and turn over of mSTG water increases during periods of colder climate as water that enters the Nordic Sea today is deviated to the south. While we can not clearly distinguish between the three temperate Atlantic sources (mSTG, MSW and ENACW) due to their almost homogeneous Nd-isotopic composition along the Northeast Atlantic margin [*Copard et al.*, 2011], it is clear, a spin up of mSTG can only occur with an accompanied retraction of mSPG to the west to allow temperate Atlantic water masses to predominate within the Porcupine Seabight.

[12] Conversely, during full interglacial conditions (MIS 1 and 5.5), stronger westerlies than today were displaced northward (~55°N) resulted in a stronger than usual subtropical high-pressure center and a deeper than normal Icelandic Low [e.g., *Hurrell and Dickson*, 2004]. This scenario led to a greater eastward extension of the mSPG (Figure 4b), essentially limiting the northward advection of temperate Atlantic mid-depth water masses (mSTG, MSW and EAAIW) into Porcupine Seabight, resulting in lower εNd values (−12 to −15; Figures 1b and 2a). Such a reinforced mSPG circulation likely promotes (i) larger salinity contrasts between mSPG and mSTG, due to a greater accumulation of heat and salinity at subtropical latitudes [e.g., *Curry et al.*, 2003; *Lozier and Stewart*, 2008], and (ii) an inflow into the Nordic seas of a relatively higher proportion of the polar waters, making this inflow fresher [e.g., *Dickson et al.*, 2002].

[13] The εNd records of cold-water corals from the Porcupine Seabight and the Gulf of Cádiz during climate stages MIS 1, 5.5, 7.4 and boundary 8/9 presented here clearly highlights the climate driven competition between mSPG and mSTG water masses as recently found in hydrographic observations but representing a by far larger range of climate dynamic. Our results suggest that further warming of the Northern Hemisphere and higher fresh water fluxes to the west will most likely further enhance the strength and eastward extension of the mSPG simultaneously reducing or confining mSTG and MSW to more temperate locations. In addition, such a confinement would reduce northwestward salt and heat export and lead to higher mid-depth temperatures and salinities. In contrast, Northern Hemisphere cooling leads to (i) a stronger northward advection of temperate Northeast Atlantic mid-depth water masses (mSTG and MSW; heat and salinity loss), and/or (ii) a potentially stronger northward flow of EAAIW, or a combination of both. Consequently, mid-depth temperatures and salinities in the Northeast Atlantic are likely reduced as heat and salt is exported further north. In addition, at deeper depth (between 2500–4600 m) periodic advances of Southern Source Water have recently been suggested by *Crocket et al.* [2011] and *Gutjahr and Lippold* [2011] during times of reduced North Atlantic overturning throughout the last glacial and MIS 2–3. Thus, further detailed studies of the past 60,000 years may lead to closely link deep and mid-depth southern source water masses in the eastern Atlantic Basin (Figure 3).

[14] Based on our results, we hypothesize a further enhancement of the mSPG and a further reduction of the northward advection of temperate Atlantic mid-depth water masses (mSTG, MSW and EAAIW) as global warming continues. This will imply a reduction of the mid-depth salt budget together with a decrease of temperature of high latitude waters for which its retro-action on North Atlantic overturning remains largely unknown today. But further warming of mid-depth waters in the temperate Atlantic may impose an additional threat to the already largely hampered growth of framework-forming corals from the Gulf of Cádiz up to the Bay of Biscay [*Frank et al.*, 2011]. However, further investigations are required to improve the time resolution of the cold-water coral εNd records and to obtain synchronous (coeval) records along the Northeast Atlantic mid-depth circulation to establish more accurately the climate influence on the mid-depth gyres.

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