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Modeling the Nd isotopic composition in the North Atlantic basin using an eddy-permitting model

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Abstract

Boundary Exchange (BE – exchange of elements between continental margins and the open ocean) has recently been emphasized as a key process in the oceanic cycle of neodymium (Nd). We here use a regional eddy-permitting resolution Ocean General Circulation Model (1/4°) of the North Atlantic basin to simulate the distribution of the Nd isotopic composition, considering BE as the only source. Results show good agreement with the data, confirming previous results obtained using the same parameterization of the source in a coarse resolution global model (Arsouze et al., 2007), and therefore the major control played by the BE processes in the Nd cycle on the regional scale. We quantified the exchange rate of the BE, and found that the time needed for the continental margins to significantly imprint the chemical composition of the surrounding seawater (further referred as characteristic exchange time) is of the order of 0.2 years. However, the timescale of the BE may be subject to large variations as a very short exchange time (a few days) is needed to reproduce the highly negative values of surface waters in the Labrador Sea, whereas a longer one (up to 0.5 years) is required to simulate the radiogenic influence of basaltic margins and distinguish the negative isotopic signatures of North Atlantic Deep Water from the more radiogenic southern origin water masses. This likely represents geographical variations in erosion fluxes and the subsequent particle load onto the continental marings. These exchange times are significantly lower than the previous evaluations using a low resolution model (6 months to 10 years), but however in agreement with the available seawater Nd isotope data, highlighting the importance of the model dynamics in simulating the BE process.

1 Introduction

The seawater neodymium Isotopic Composition (Nd IC, or ε_{Nd}) varies in the ocean in close relation to the oceanic circulation. ε_{Nd} is the part per 10 000 deviation of the observed $^{143}Nd/^{144}Nd$ ratio from that of the bulk earth (Jacobsen and Wasserburg, 1980).

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Relatively negative ε_{Nd} values are observed in the North Atlantic Ocean, increasing along the path of the global thermohaline circulation up to more radiogenic values in the North Pacific (Piepgras and Wasserburg, 1980; Lacan and Jeandel, 2005a). Changes in Nd IC observed in the water column are related to vertical distribution of water masses. In the Atlantic ocean, the North Atlantic Deep Water (NADW) is characterized by a relatively homogeneous ε_{Nd} value ranging from −13 to −14, whereas the Antarctic Intermediate Water (AAIW) and Antarctic Bottom Water (AABW) are characterized by more radiogenic end-member isotopic signatures of approximately −8 ε_{Nd} prior to any mixing with other Atlantic water masses (Piepgras and Wasserburg, 1987; Jeandel, 1993). ε_{Nd} is considered to be a "quasi-conservative" tracer (ε_{Nd} values are conserved for sites distant from source regions) and is used to tag water masses with distinct isotopic compositions in order to constrain water mass mixing and pathways, and the strength of the global thermohaline circulation in paleoceanography.

Nd sources to the ocean are lithogenic, and the mean Nd IC of a basin is representative of the surroundings continents (Albarede et al., 1997; Jeandel et al., 2007). However, the process leading to the transfer of Nd from the continents to the ocean is still an open debate. Nevertheless, it is generally admitted that the role of hydrothermal inputs is negligible because Nd, as well as all Rare Earth Elements (REE), are effectively scavenged at hydrothermal sites (Michard et al., 1983). It has also been shown that atmospheric dusts and river discharge alone cannot account for both the distributions of Nd IC and Nd concentration, (Tachikawa et al., 2003; Van de Flierdt et al., 2004, Arsouze et al., 2009). Finally, Lacan and Jeandel (2005a) proposed the *Boundary Exchange* (BE, exchange of elements between water masses and sediments deposited along continental margins) as an important term in the budget of REE in the ocean.

The identification of Nd sources in the North Atlantic basin has been particularly challenging. Lacan and Jeandel (2005b) confirmed the need to invoke terrigenous inputs originating from the particulate discharge along the Southern Greenland continental margin (distinguished by a very unradiogenic composition), as well as water-mass mixing, to explain the characteristic unradiogenic signature of the NADW. This conclusion complements results from several other studies that also evidenced the influence of BE as a source to explain changes in isotopic signature of water masses in this basin (Lacan and Jeandel, 2004a, b, 2005b). More recently, Rickli et al. (2009) also confirmed this hypothesis. Therefore, the North Atlantic basin is a relevant region to test the impact of BE on the $\varepsilon_{\mathrm{Nd}}$ oceanic distribution. The high density of observations available, and the importance of this region to the thermohaline circulation, which is of particular interest to study past variations of global circulation, also make this the ideal region to evaluate the role of BE on the regional scale.

A first attempt to model global Nd IC distribution using a coarse resolution model ($2^\circ \times 2^\circ \cos(\mathrm{lat})$) underlined that BE was an important process among the sources of Nd to the ocean (Arsouze et al., 2007). In these simulations, the global $\varepsilon_{\mathrm{Nd}}$ gradient between high $\varepsilon_{\mathrm{Nd}}$ in the Pacific and low $\varepsilon_{\mathrm{Nd}}$ the Atlantic was reproduced, but discrepancies with data were observed in the North Atlantic Ocean where the simulated Nd isotopic signature was too radiogenic. Invoking dusts or dissolved river inputs could not help to decrease the modeled Nd signature, since these sources are themselves too radiogenic to explain the observed negative signal (Lacan and Jeandel, 2005b). Other possibilities explaining the offset between the simulated distribution and data in the North Atlantic are an under-estimation of the influence of the BE, particularly with the non radiogenic margins in Greenland and along North Canada, or an incorrect representation of the circulation's dynamics in the region. Indeed, although the use of a coarse resolution model was a good compromise for our first global modeling study, such resolution prevented a good representation of boundary currents, simulated as too slow and too diffusive, in particular in the North West Atlantic.

Other global modeling studies contributed to improve our understanding of the oceanic Nd cycle. Jones et al. (2008) showed that $\varepsilon_{\mathrm{Nd}}$ distribution in the Atlantic basin could be explained via water mass mixing, hence confirming the quasi-conservative property of the Nd IC tracer. Siddall et al. (2009) emphasized the role of the sinking particles in the water column to reconcile both Nd concentration and IC distribution, using a reversible scavenging model. However, both studies prescribed surface Nd

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concentration and IC, therefore not focusing on of the question of the Nd sources into the ocean, which is a prerequisite for the application of ε_{Nd} as a water mass tracer. More recently Arsouze et al. (2009) used a coupled global dynamical/biogeochemical model in order to propose an explicit modeling of both Nd concentration and IC distribution. These authors confirmed that BE is the dominant Nd source to the ocean (more than 95% of the total input), but also evidenced that river inputs and atmospheric dusts are significantly constraining the surface water ε_{Nd} values in some areas.

The present study proposes the first simulation of the distribution of ε_{Nd} values using an eddy-permitting model, on a regional scale (the North Atlantic basin). Our aim is to estimate the influence of BE on a regional scale on ε_{Nd} distribution, and to determine the timescale on which this process acts at such regional scales when compared to previous estimates on global scale (Arsouze et al., 2007). It is of particular interest because it may help to constrain the processes involved in this exchange. On the one hand, high resolution and good representation of boundary currents at the ocean margins are essential in order to improve simulation of processes occurring at the sediment/water interface: this justified the use of an eddy permitting model 1/4°. On the other hand, the explicit representation of the tracer sources and sinks proposed in Arsouze et al. (2009) was hardly applicable in this configuration regarding to the induced high computational cost. We therefore adopted a similar approach to that of Arsouze et al. (2007), i.e. considering BE as the only Nd source, parameterized via a relaxation term along the continental margin.

2 Description of the model and ε_{Nd} modeling

We use the NEMO numerical model (Madec 2008), in the regional eddy permitting configuration NATL4, extracted from the global 1/4° configuration ORCA025 (The Drakkar Group, 2007; Le Sommer et al., 2009). The domain includes the North Atlantic basin and Nordic Seas, extending from 20° S to 80° N in latitude, and up to 23° E in Mediterranean. Buffer zones are prescribed on the open boundaries of the domain. The vertical resolution (46 levels) ranges from 6 m in the upper layer, to 250 m at depth. We use partial-steps to adjust the last numerical level with the bathymetry.

The dynamic simulation is integrated for 20 years (1980 to 2000) from a climatological initial condition (Levitus et al., 1998) and using the Drakkar interannual atmospheric forcing DFS3. All ε_{Nd} simulations were run "offline", using the passive tracer model (Ethé et al., 2006), using the last 10 years of the pre-calculated dynamical fields (output averaged every 5 days), providing a statistical mean state of the ocean circulation. The tracer is then integrated until equilibrium is reached (i.e. 60 years, cycling 16 times over the dynamical fields).

Comparison of the dynamical features simulated by the model between global coarse and regional eddy-permitting resolution shows large differences. Indeed, the transports are comparable in both configurations but the currents are much more vigorous in the eddy-permitting configuration. Barnier et al. (2006), Penduff et al. (2007), and Le Sommer et al. (2009) show how the use of an energy- and enstrophy-conserving momentum advection scheme in NEMO at 1/4° yielded a clear improvement in the simulation of current-eddy-topography interactions, and thus of along-topography circulations. Comparisons between a large current meter database (Holloway, 2008) and two DRAKKAR global ocean simulations (T. Penduff, personal communication, 2009) confirm that increasing NEMO's resolution from 2° to 1/4° yields a large reduction of local model-observation mismatches, both in terms of mean current strengths (which increase toward observed levels) and directions (aligning with measured flows more nearly along isobaths), in particular along basin margins where many current meters are located.

Arsouze et al. (2007), in the global configuration of the model, defined BE as a source/sink term, $S(\varepsilon_{Nd})$, in the equation of conservation of the tracer, that is parameterized by a relaxation term between the continental margin and the ocean:

$$S(\varepsilon_{Nd}) = 1/\tau \cdot \left(\varepsilon_{Nd_{mar}} - \varepsilon_{Nd}\right) \cdot \mathrm{mask}_{mar} \quad (1)$$

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where τ is the characteristic relaxing time, $\varepsilon_{Nd_{mar}}$ is the ε_{Nd} value of the material deposited along the continental margin, $mask_{mar}$ is the percentage of surface bathymetry in a numerical grid cell of the model (determined using the 1 min resolution bathymetry Gebco) and ε_{Nd} is the Nd IC value of the ocean. In the following experiments, we use the same parameterization as equation (1), refining the scale of the interpolation of $\varepsilon_{Nd_{mar}}$ value compared to the map used on global scale using data compilation by Jeandel et al. (2007), and with $mask_{mar}$ recalculated on the NATL4 grid. We thus only model Nd IC, and make the implicit hypothesis of a constant Nd concentration. By definition from Eq. (1), τ is the timescale of the BE as defined previously, i.e. the time needed for processes to transfer chemical properties from the continental margin to the overlaying water-mass.

Because this is not a global GCM we have model boundaries in the open ocean in the high North Atlantic and South Atlantic that must be prescribed. We prescribe ε_{Nd} values for these "open ocean boundaries" using literature data from Signature 29 and Signature 30 data in the North Atlantic (Lacan and Jeandel, 2004a, c), and SAtl 217, SAtl 271 and SAtl 302 data at the South Atlantic (Jeandel, 1993). Prescribing these open ocean boundary conditions is similar to applying a relaxing term with a short characteristic relaxing time, which tags waters entering the basin with a Nd IC consistent with observations.

Four tests on the characteristic relaxing time are performed: experiments EXP1, EXP2, EXP3 and EXP4 have τ=1 day, 0.2 year (2.4 months), 0.5 year (6 months), and 1 year, respectively (cf. Table 1). In a last experiment (EXP5), we explore the possibility that our BE parameterization might be dependant on the mineralogical maturity of margin sediments (e.g. granitic vs. basaltic). We tested this by scaling the characteristic exchange time (τ) to the Nd IC of the margin ($\varepsilon_{Nd_{mar}}$), so that exchange occurs faster along basaltic margins. We included this test because basaltic sediments contain minerals that are unstable at the Earth's surface and thus erode much faster than granitic sediments (Amiotte Suchet et al., 2003; Dessert et al., 2003). Hence, τ is set to vary linearly from 0.1 years for the most radiogenic Nd IC values ($\varepsilon_{Nd_{mar}}$=+8 along the Iceland margin) to 0.5 years for the most non-radiogenic values ($\varepsilon_{Nd_{mar}}=-38$ on the South-East Greenland). This parameterization might be too simplistic, but the current knowledge of the processes involved in sediments' dissolution does not allow for a more sophisticated implementation. Finally, for comparison purpose with the present sensitivity tests, we present an extraction of the North Atlantic basin from a previous simulation (Arsouze et al., 2007) in the ORCA2 ($2^{\circ}\times2^{\circ}\cos(\mathrm{lat})$) configuration with a relaxing time of 1 year.

3 Results

The simulated ε_{Nd} distributions are in good agreement with the data (Figs. 1, 2, 3 and 4, Table 1), though BE is considered as the only source of Nd to the ocean. More specifically experiments EXP2 and EXP3 (relaxing time of 0.2 years and 0.5 years respectively) simulate in both cases 76% of the observed ε_{Nd} values with ±3 unit accuracy (and almost 40% with $\pm1\varepsilon_{Nd}$, Fig. 1 and Table 1), with correlation coefficients close to 0.65, and a standard deviation very close to the data for EXP2 (Fig. 1). The remaining errors affecting the simulated values are mainly corresponding to surface or sub-surface samples located close to radiogenic coastal shelves, in particular along the Greenland – Iceland – Scotland ridge (Fig. 3).

These results are in better agreement than in the previous coarse resolution global modeling (ORCA2), with a relaxing time of 1 year (68% and 32% within ±3 and ±1 units errors respectively, Fig. 1). These simulations generated strong geographical gradients in ε_{Nd}, particularly in surface waters along the continental margins (leading to patchy effects), suggesting an overestimation of the exchange (Figs. 3 and 4 in Arsouze et al., 2007). Contrastingly, the regional eddy-permitting resolution (NATL4) simulation with the same relaxing time (1 year) leads to a homogeneous distribution in surface waters (Fig. 2, EXP4, Table 1). An extremely short relaxing time of 1 day (EXP1) leads to large disparity in simulated ε_{Nd} values, including non-realistic radiogenic extremes near Iceland-Scotland and Caribbean Sea. Our first experiment (EXP1) is the only

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experiment that successfully simulates the observed negative ε_{Nd} values in surface waters of Labrador Sea (Fig. 2).

At depth (Fig. 4), all simulations EXP2, EXP3 and EXP4 (τ=0.2 year, 0.5 year and 1 year respectively) display comparable features, in good agreement with the data. In particular these deep results are much closer to the data than those obtained with ORCA2. Experiment τ=1 day (EXP1) generates deep waters that are too negative.

(EXP5) was run assuming that volcanic margins are releasing their Nd more than the granitic ones, volcanic fields being known to be more easily weathered than granitic ones. This experiment generates seawater ε_{Nd} that is globally too radiogenic in the basin, both in surface and at depth (Figs. 1, 2, 3 and 4), particularly along the Caribbean arc and the Iceland-Scotland ridge.

Consistently with the results obtained with the global scale simulations, we find that a long characteristic exchange time induces longer residence time, and finally more homogeneous ε_{Nd} values in the basin, at all depths.

4 Discussion

The results presented here confirm on a regional scale what has been previously suggested on a global scale: by assuming BE as the only Nd oceanic source term, it is possible to reproduce the main features of the distribution of its isotopic composition in the basin. This reinforces the preceding conclusions on BE as an important process in the Nd oceanic cycle.

One striking difference between these results and our previous results (Arsouze et al., 2007) is that the ideal characteristic exchange time τ is much shorter when deduced from eddy-permitting resolution simulations (NATL4) than from coarse resolution ones (ORCA2). The coarse resolution configuration (ORCA2) yielded an ideal exchange time varying from 6 months in surface to 10 years at depth. The most realistic reproduction of ε_{Nd} distribution for the eddy-permitting model uses a relaxing time of 0.2 or 0.5 years, or even of the order of few days in surface and subsurface to correctly reproduce the highly non-radiogenic waters in the Labrador Sea. This very short relaxing time implies a very intense exchange with the margins of the studied region. The rapid exchange rates suspected here are consistent with recent ε_{Nd} data that suggest an input from continental margins within only few weeks at the Kerguelen Islands, another region where high dynamical forcing is present (Zhang et al., 2008).

The short relaxing time required to accurately represent BE could reveal that sources other than BE -and not represented here- are missing. Indeed, even if BE is largely dominating the other sources of Nd to the ocean (about 90%; Tachikawa et al., 2003; or more, Arsouze et al., 2009), surface waters Nd IC distribution is for the most part reflecting river and aerosols inputs (Piepgrass and Wasserburg, 1987; Arsouze et al., 2009). However, the northern part of the Atlantic is barely affected by these two kinds of sources. Indeed, Lacan and Jeandel (2005b) showed that dissolved river input and atmospheric dusts can rarely account for missing source in the Nordic Seas or in the Labrador Sea because (1) their IC are not compatible with the shift observed along the water-mass path, and/or (2) their total input is much lower than the flux required to reproduce the observed isotopic gradient. For example, these authors estimated that dissolved rivers discharges and atmospheric dust inputs account for only 8% and 1% of the observed isotopic signature change along the path of formation of the North West Atlantic Bottom Water (at 2700 m depth), respectively. However, these last sources might have some local effects in surface-subsurface waters. Though limited, the influence of these sources in the ε_{Nd} distribution could lead to the largest discrepancies observed when compared with the data near continents.

This short characteristic exchange time found with the regional modeling likely reflects the reproduction of boundary currents more realistic and vigorous in NATL4 than in ORCA2. Sluggish water masses and important diffusion generated in the ORCA2 configuration (Dutay et al., 2004) overestimate the residence time of water masses in contact with continental margins and thus enhance the local influence of the margin isotopic signature. Thus, simulation with a relaxing time of 1 year in ORCA2 configuration leads to strong geographical gradients, whereas simulation using the same relaxing time in the NATL4 configuration leads to a nearly homogenized basin. This underscores the importance of *Boundary Currents* representation to simulate the *Boundary Exchange* and the resulting ε_{Nd} distribution. Note that although improved relative to ORCA2, boundary currents in NATL4 are not realistic enough yet to warrant a more detailed examination of the ε_{Nd} model-data misfit. For example, there is too much entrainment in the modeled Denmark Strait overflow, which alters the dynamics and properties of the Lower North Atlantic Deep Water downsteam (this is a familiar flaw in models with geopotential vertical coordinates, e.g., Willebrand et al., 2001).

EXP5 suggests that in the studied area, the BE process does not seem to be more sensitive to basaltic than to granitic margin sediments. This observation does not assess that margin-to-water inputs of Fe or Nd in this area that are suspected to result from lithogenic silicate dissolution (Lacan and Jeandel, 2005a; Moore and Braucher, 2008; Jeandel et al., 2010) are favored by the high solubility of basalts (Dessert et al., 2003). Nevertheless, this last result has to be taken cautiously because the parameterization used between BE and the margin lithology might be too simplistic

Shortcomings are also remaining in EXP2 (best correspondence with data within all sensitivity tests performed in this study, Table 1, Figs. 1 and 2). The main discrepancy resides in the very radiogenic Caribbean Islands that over-imprint the water masses in the southwestern part of the domain, despite the occurrence of unradiogenic continents surrounding the Caribbean Sea. This was also observed with the global model (ORCA2). However, there is no Nd data in the Caribbean Sea, so that we cannot confirm this result. Further documentation of this area (as planed in the framework of GEOTRACES program for example) would help to better understand the possible BE sensitivity to the lithology of the margin sediment, sensitivity suspected to be important based on seawater data from the Greenland – Scotland (Lacan and Jeandel, 2004a,b). Production of non-realistic radiogenic values in this area is likely due to overestimated inputs from this basaltic ridge, reflecting biases in the parameterization of the continental margin. In order to reduce these artifacts, and also explain the large geographical variations observed in the value of the characteristic exchange time, it might be useful

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to couple this BE parameterization to a geographical sediment delivery map, rather than to a topographic one.

5 Conclusions

In this study, ε_{Nd} distribution was simulated using the regional NEMO/NATL4 eddy-permitting model in the North Atlantic Ocean. Boundary Exchange (BE) parameterization was performed via a relaxing term.

Characteristic margin-to-ocean exchange time is re-estimated to be between few days and 6 months in the NATL4 configuration, significantly shorter than previous estimations of 6 months to 10 years, estimated from the global low resolution ORCA2. The reduced exchange time and the inclusion of the eddy permitting model yielded results that are in better agreement with the available data, especially largely improving the Nd isotopic signature of the deepest water masses. This work highlights the dependency of the parameterization of BE to the model and dynamics used. In particular, a better reproduction of *Boundary Currents* in the NATL4 configuration compared to ORCA2 configuration is a key factor to better estimate the characteristic exchange time of the *Boundary Exchange* process and to improve the simulation of marine Nd isotopes. Ongoing work on the reproduction of overflows and on configurations of the model at a higher resolution will produce a more realistic representation of boundary currents, and subsequently help refining the BE time scale.

However, this important model-dependency does not undermine the importance of the BE hypothesis. Instead, even if we cannot rule out the importance of any other source of Nd in the basin, we found that considering the source of the BE as the only Nd oceanic input term leads to a very satisfying Nd IC distribution that closely matches observations in the whole basin. Available data in the region (Lacan, 2002) and global modeling (Arsouze et al., 2009) suggest that sediment remobilization, rather than hydrothermal inputs, atmospheric dusts or even dissolved river inputs, might be the dominant term in the ocean Nd sources associated with the BE. Determining its behavior

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and the parameters acting on the BE requires further studies, that are necessary to understand the geographical variations of this process.

Hence, we confirm on regional scale what has been previously suggested on local scale (via field observations) and global scale (via global modeling): Boundary Exchange is an important process in the cycling of Nd in the ocean.

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Table 1. Summary of the main characteristics for each experiment.

Experience	Relaxing time τ	Percentage of points that reproduce the data with a $\pm 3\varepsilon_{Nd}$ accuracy	Percentage of points that reproduce the data with a $\pm 1\varepsilon_{Nd}$ accuracy	Regression coefficient for data/model points
EXP1 (NATL4)	1 day	57.91	25.63	1.231
EXP2 (NATL4)	0.2 year	75.63	33.54	0.7227
EXP3 (NATL4)	0.5 year	74.68	38.92	0.5708
EXP4 (NATL4)	1 year	73.73	38.61	0.4553
EXP5 (NATL4)	0.1 year (max $\varepsilon_{Nd_{mar}}$) to 0.5 year (min $\varepsilon_{Nd_{mar}}$)	57.91	25.95	0.5564
ORCA2	1 year	68.04	32.28	0.6693

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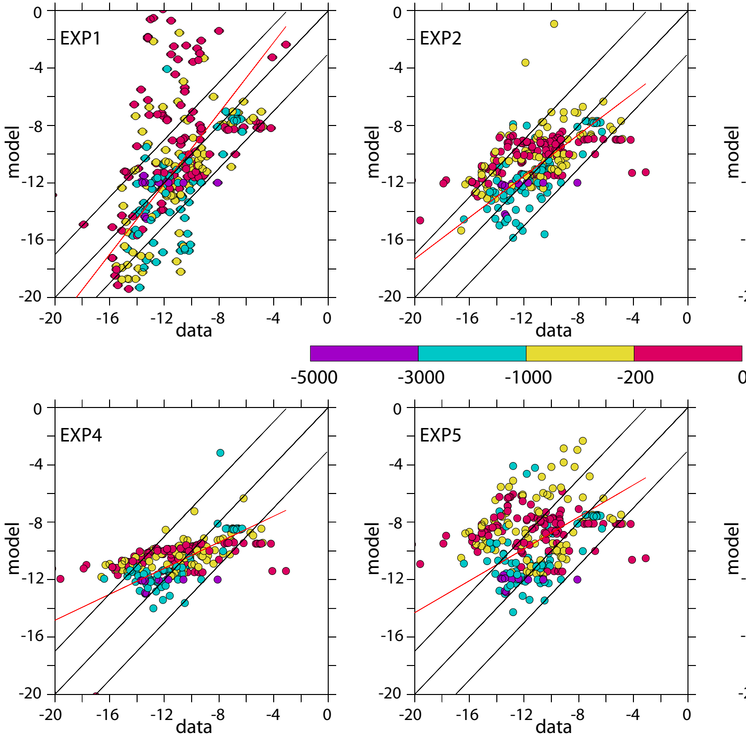

Fig. 1. Model/data comparison as a function of depth (color code) for the 5 simulations performed with the model in NATL4 configuration. The extraction in the North Atlantic from a previous simulation using the global ORCA2 configuration, with a relaxing time of 1 year, is also shown. Red line is the linear regression of the points. Diagonal black lines are lines ε_{Nd} (modeled)=ε_{Nd} (data), ε_{Nd} (modeled)=ε_{Nd} (data)+3ε_{Nd} and ε_{Nd} (modeled)=ε_{Nd} (data)−3ε_{Nd}. In EXP5, relaxing time varies from τ=0.1 years for margins associated with a "high ε_{Nd}" value (=+8), to a relaxing time of τ=0.5 years for margins associated with a "low ε_{Nd}" value (=−38). A linear relationship is set between those two extrema values. Main statistical characteristics for each experiment are reported in Table 1.

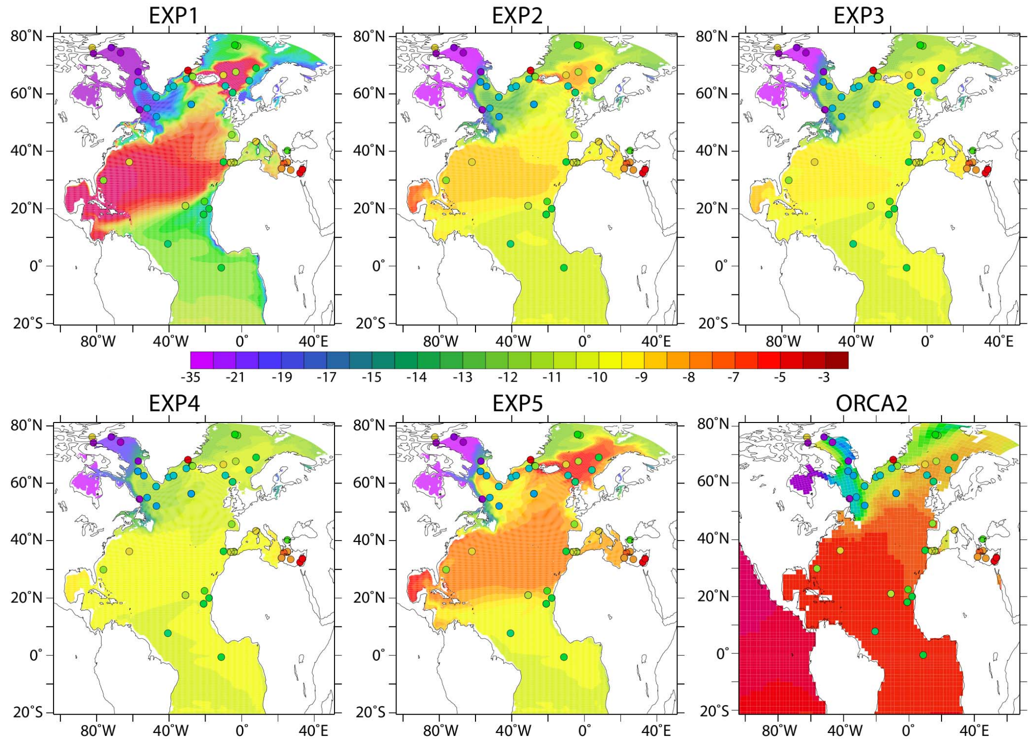

Fig. 2. 100 m-depth ε_{Nd} distribution map, for the 5 simulations performed using the model in NATL4 configuration. EXP1: A map of the ε_{Nd} distribution at the same depth, from a previous simulation using the global ORCA2 configuration, with a relaxing time of 1 year, is also shown. Superimposed circles represent the data between 50 and 300 m depth. Color scale is the same for both simulation output and data, and is nonlinear. Data are issued from Piepgras and Wasserburg (1980, 1983, 1987), Stordal and Wasserburg (1986), Spivack and Wasserburg (1988), Tachikawa et al. (1999), Lacan and Jeandel (2004a,b,c, 2005a,b), Dahlqvist and Andersoon (2005) and Rickli et al. (2009) and compiled by F. Lacan and K. Tachikawa (available here: http://www.legos.obs-mip.fr/fr/equipes/geomar/results/database_may06.xls).

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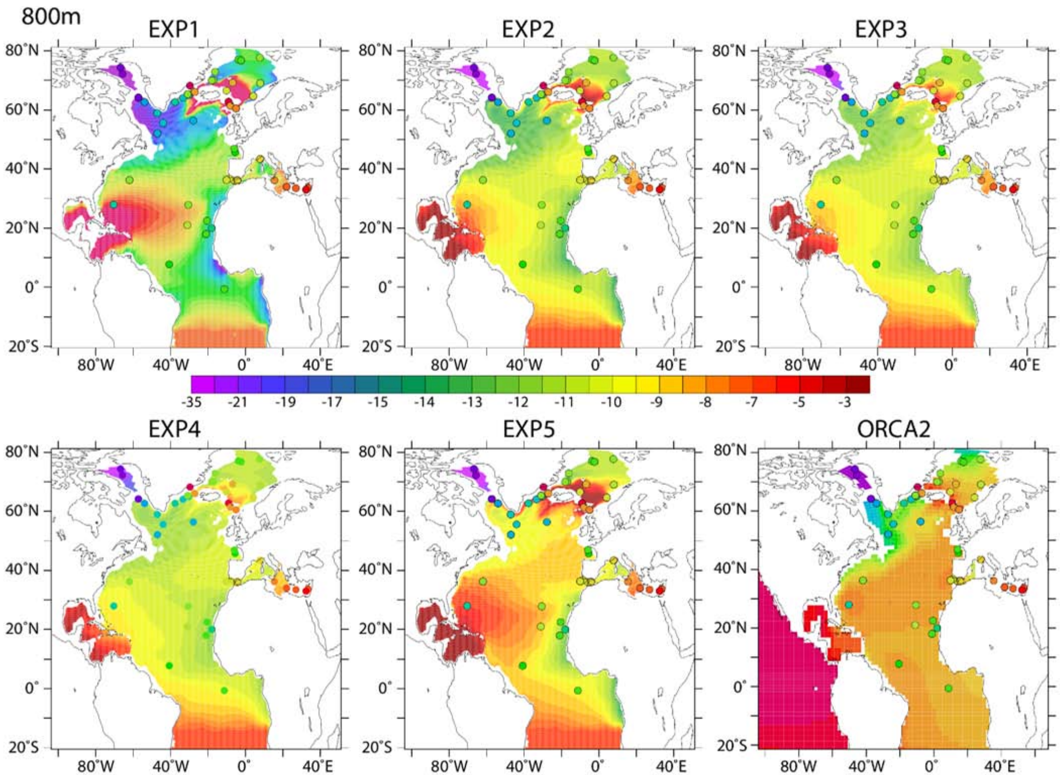

Fig. 3. Same as Fig. 2, but at 800 m depth. Data plotted (circles) are from 500 to 1000 m depth. Data are issued from Piepgras and Wasserburg (1980, 1983, 1987), Stordal and Wasserburg (1986), Spivack and Wasserburg (1988), Tachikawa et al. (1999), Lacan and Jeandel (2004a,b,c, 2005a,b), Dahlqvist and Andersoon (2005) and Rickli et al. (2009) and compiled by F. Lacan and K. Tachikawa (available here: http://www.legos.obs-mip.fr/fr/equipes/geomar/results/database_may06.xls).

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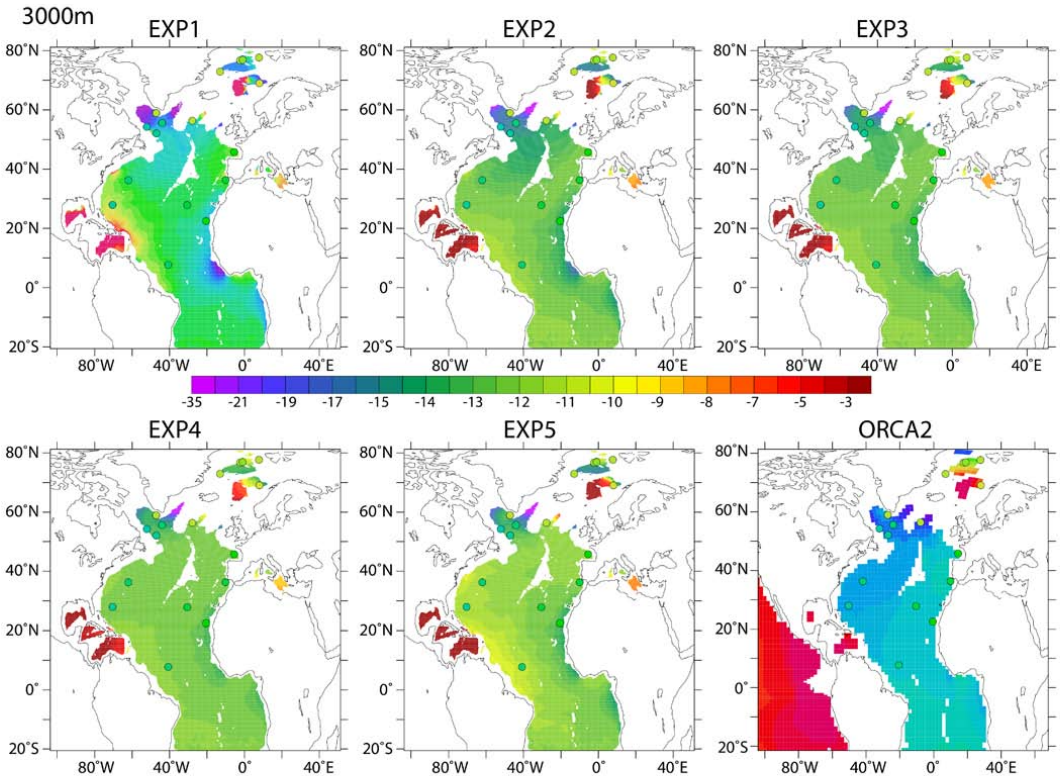

Fig. 4. Same as Fig. 2, but at 3000 m depth. Data plotted (circles) are from 2500 to 3500 m depth. Data are issued from Piepgras and Wasserburg (1980, 1983, 1987), Stordal and Wasserburg (1986), Spivack and Wasserburg (1988), Tachikawa et al. (1999), Lacan and Jeandel (2004a,b,c, 2005a,b), Dahlqvist and Andersoon (2005) and Rickli et al. (2009) and compiled by F. Lacan and K. Tachikawa (available here: http://www.legos.obs-mip.fr/fr/equipes/geomar/results/database_may06.xls).

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