Improvements of simulated Western North Atlantic current system and impacts on the AMOC

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Abstract:

Previous studies have shown that low horizontal resolution (of the order of 1°) ocean models, hence climate models, are not able to adequately represent boundary currents nor mesoscale processes which affect the dynamics and thermohaline circulation of the ocean. While the effect of mesoscale eddies can be parameterized in low resolution models, boundary currents require relatively high horizontal resolution. We clarify the impact of increasing the resolution on the North Atlantic circulation, with emphasis on the Atlantic Meridional Overturning Circulation (AMOC), by embedding a 1/8° nest covering the North Atlantic into a global 1/2° model.

Increasing the resolution in the nest leads to regional improvements of the circulation and thermohaline properties in the Gulf Stream area, for the North Atlantic Current, in the subpolar gyre and the Nordic Seas, consistent with those of previous studies. In addition, we show that the Deep Western Boundary Current dense water transport increases with the nest, from the overflows down to Flemish Cap, due to an increase in the Denmark Strait overflow as well as dense water formation in the subpolar gyre. This increases the Atlantic Meridional Overturning Circulation in density space by about 8 Sv in the Subpolar gyre in the nested configuration. When exiting the Labrador Sea around 53°N we illustrate that the Deep Western Boundary Current successively interacts with the upper ocean circulation composed with the North Atlantic Current in the intergyre region, the Northern Recirculation Gyre, and the Gulf Stream near Cape Hatteras. This surface/deep current interaction seems to induce an increase of the AMOC intensity in depth-space, giving rise to an AMOC maximum near 35°N. This process is missing in the configuration without nesting. At 26.5°N, the AMOC is 4 Sv larger in the nested configuration and is in good agreement with observations. Finally, beyond the nest imprint (i.e. in the low resolution area) in the South Atlantic the AMOC maximum at 40°S is 3 Sv larger at the end of the simulation meaning that information is able to propagate outside the nest without being fully damped. This underlines the benefit of using the nest for a reasonable computing time compared to a fully global higher resolution configuration.

Highlights

► Two global simulations that differ in their resolution in the North Atlantic are compared. ► At high resolution, the dynamics as well as thermohaline properties are improved. ► DWBC intensity and pathway compare better with observations in the higher resolution. ► The AMOC- σ is 8 Sv larger in the high resolution simulation. ► Interaction between surface and deep currents contributes to increasing the AMOC-z.

Keywords : Deep Western Boundary Current ; Atlantic Meridional Overturning Circulation ; North Atlantic Current ; Gulf Stream ; Subpolar Gyre

1 1. Introduction

2 With respect to the ocean's contribution to climate, namely the transport
 3 of heat from the equator poleward, the Atlantic Ocean stands out as it trans-
 4 ports heat northward in both hemispheres. This transport is associated with
 5 the Atlantic Meridional Overturning Circulation (AMOC) that combines a
 6 northward near-surface flow (from the surface down to approximately 1000
 7 m depth), referred to as the "upper limb", with a compensating southward
 8 flow at depth known as the "lower limb". The latter is mainly composed of
 9 the Deep Western Boundary Current (DWBC) carrying North Atlantic Deep
 10 Waters (NADW). The AMOC is thought to play a key role in the Earth's
 11 climate system (Srokosz et al., 2012), but it remains unclear what controls its
 12 strength and structure. Various modeling experiments have been developed
 13 to complement existing observations in this perspective.

14
 15 Coupled climate models are useful to investigate climate change issues
 16 because they are able to simulate past and present climate, where they can
 17 be evaluated against observations, and attempt to predict future climate as-
 18 suming scenarios for external (including anthropogenic) forcings. Because
 19 these models combine various components of the Earth's climate, and must
 20 be spun up for long time periods to reach equilibrium, ocean and atmosphere
 21 components have resolutions of the order of 1° (as for the 5th phase of the
 22 Coupled Model Intercomparison Project). At this resolution, many oceanic
 23 processes are not explicitly resolved which leads to major well-known biases,
 24 in particular along oceanic western boundaries. Griffies et al. (2009) present a
 25 review of those biases based on an intercomparison of forced ocean models at

26 this resolution. In the North Atlantic subtropical gyre, the separation of the
 27 Gulf Stream from the American East Coast, near Cape Hatteras, is not well
 28 reproduced by these models. As the simulated Gulf Stream follows the coast
 29 north of Cape Hatteras, a warm bias is observed in place of the relatively
 30 cold Northern Recirculation Gyre. In the intergyre region, the simulated
 31 North Atlantic Current (NAC) tends to flow eastward offshore Grand Banks
 32 without forming the well-observed NorthWest Corner (NWC). This results in
 33 a large cold and fresh anomaly off Newfoundland, also called "the Blue spot
 34 of death" by modelers (Gnanadesikan et al., 2007). In atmosphere-ocean
 35 coupled models, these oceanic anomalies significantly affect the atmospheric
 36 circulation, which influences the ocean in return via biases in surface buoy-
 37 ancy fluxes over the subpolar gyre (Weese and Bryan, 2006). Indeed, the
 38 peak winter mixed layer depths at high latitudes in the North Atlantic are
 39 most often badly located and/or overestimated in low-resolution ocean and
 40 climate models compared to observations; the overestimation may be due to
 41 the lack of restratification processes (Chanut et al., 2008). Because these
 42 oceanic biases have different signatures depending on model settings and pa-
 43 rameters, the ocean model experiments by Griffies et al. (2009), albeit forced
 44 by the same atmospheric conditions, have very different AMOC strength and
 45 structure.

46
 47 Numerical developments are underway to improve low resolution ocean
 48 models, developing parameterizations of unresolved processes or improving
 49 numerical schemes. For example, Penduff et al. (2007) illustrate the im-
 50 provements of DWBC structure and intensity in a global $1/4^\circ$ configuration,

51 obtained when combining partial steps (better representing the ocean topog-
 52 raphy) and an energy-enstrophy conserving momentum advection scheme
 53 (Le Sommer et al., 2009). Nevertheless, there are key physical processes
 54 for AMOC that cannot be easily reproduced nor mimicked. The large-scale
 55 adjustment of AMOC to dense water formation seems to be initiated by
 56 the propagation of Kelvin waves and/or topographic waves along the west-
 57 ern boundary, as suggested by theoretical numerical experiments (Herbaut
 58 et al., 2006; Johnson and Marshall, 2002); the grid resolution and lateral
 59 viscosity are known to affect the propagation of such waves (Hsieh, 1983).
 60 Restratification of the upper ocean, after dense water formation by convec-
 61 tion, involves mesoscale (Chanut et al., 2008; Katsman et al., 2004) and
 62 submesoscale processes (Fox-Kemper and Ferrari, 2008). Finally, subtrop-
 63 ical and subpolar western boundary currents are intrinsically trapped in a
 64 layer where viscosity, lateral friction and non-linearities cannot be neglected.
 65 Several studies have attempted to clarify the impact of small scale processes
 66 on the large-scale circulation in the North Atlantic, by comparing models
 67 of varying resolution. Smith et al. (2000) and Bryan et al. (2007) suggest
 68 that a resolution of $1/10^\circ$ or higher is needed to reproduce the Gulf Stream
 69 separation properly. Treguier et al. (2005) investigate four ocean models of
 70 resolution spanning $[1/6^\circ - 1/12^\circ]$ in the subpolar gyre, and suggest that
 71 increased horizontal resolution allows a better representation of large scale
 72 ocean features. Spence et al. (2012) also find that the representation of west-
 73 ern boundary currents is improved with resolution. Because these regional
 74 circulation features contribute to AMOC, their improvement is beneficial to
 75 the accurate simulation of AMOC. Our objective is to revisit these regional

improvements due to increased resolution, in order to clarify their impact on AMOC.

The impact of spatial resolution on AMOC has been investigated by Hodson and Sutton (2012) in a coupled ocean-atmosphere model: they compare experiments after increasing the horizontal resolution of the ocean from 1° to $1/3^\circ$ (atmospheric resolution is increased as well, from 1.25° latitude x 1.875° longitude to 0.83° x 1.25°). They find that the AMOC structure and strength is similar between both experiments, which may be due to the fact that their "high" oceanic resolution does not resolve mesoscale processes in the North Atlantic at subtropical and higher latitudes, and hence remains in the "eddy-permitting" regime. Here, we increase horizontal resolution from $1/2^\circ$ x $1/2^\circ \cos\phi$ to $1/8^\circ$ x $1/8^\circ \cos\phi$ (ϕ latitude) in the North Atlantic, extending the eddy-resolving regime over the subtropical gyre. This ensures a substantial improvement of Gulf Stream dynamics, which has repercussions for the whole North Atlantic and, subsequently, the AMOC, which contrasts with Hodson and Sutton's (2012) results. Rather than increasing the resolution of our whole global ocean model, which is expensive even in forced mode, we develop a configuration that includes a fully interactive nest covering the North Atlantic. This ocean configuration is forced by atmospheric reanalyses; thus we cannot investigate the impact of improved western boundary currents on the atmosphere. Still, this study may be useful in improving climate models as it demonstrates how increasing spatial resolution improves North Atlantic circulation and AMOC. The original model configuration, as well as experiments and forcings, are described in section 2. In section 3,

we highlight regional improvements, similar to those obtained in previous studies. Then we demonstrate their impact on the AMOC (section 4). We discuss our results in conjunction with those of previous studies, including Hodson and Sutton (2012), in section 5, and then conclude (section 6).

2. Model configuration

Experiments analysed hereafter are set-up with the NEMO modeling platform (Madec, 2008), using the OPA Ocean General Circulation Model (OGCM) and sea-ice LIM2 components associated with Adaptative Grid Refinement In Fortran (AGRIF) (Debreu et al., 2008) capability. Three simulations presented in this study rely on two configurations that only differ in horizontal resolution in the North Atlantic.

2.1. Domain and grid characteristics

In this paper we refer to three numerical experiments. Two of them rely on global configurations at $1/2^\circ$ named ORCA_REF and ORCA_NOG; the first is our reference experiment, the second is a sensitivity experiment which differs from ORCA_REF only by the omission of the Gent and McWilliams parameterization. The third experiment is called ERNA and is the highlight of this study.

In detail, ORCA_REF and ORCA_NOG are based on the ORCA tripolar and quasi-isotropic grid (Madec, 2008) at $1/2^\circ$ nominal resolution at the equator with 722x551 grid points (Biaostoch et al., 2008). ERNA combines a coarse grid that is the same as ORCA_REF, with a higher-resolution grid covering the North Atlantic from 20°N to 75°N (Fig. 1). A spatial grid ratio

of 4 allows the model to reach a $1/8^\circ$ resolution over this area with 724×632 grid points. The "two-ways" interaction between fine and coarse grids in ERNA allows the exchange of information along lateral boundaries of the nest (for 3D variables including the baroclinic transport of mass, heat and salt) and over the whole surface of the nest (for 2D variables such as the barotropic transport and sea-ice characteristics). The sea-ice is explicitly simulated in both coarse and fine grids. The ORCA $1/2^\circ$ coarse grid is marginally "Eddy-Permitting" in equatorial regions. The $1/8^\circ$ grid fully resolves mesoscale eddies from the southern boundary of the domain to 45°N and can be considered "Eddy-Permitting" northward. Experiments share the same 64 vertical geopotential levels with an increasing cell thickness from 6 m near the surface to around 200 m in the deep ocean. The last level thickness just above the sea floor adjusts to the actual topography which allows a better representation of bathymetry (Barnier et al., 2006). The bathymetry is interpolated from ETOPO2v2 below 300 m depth and GEBCO One minute grid, version 2.0 in coastal areas, with no horizontal smoothing (except when required by AGRIF along the lateral boundaries of the nest).

2.2. Numerical aspects

The model solves the three-dimensional Primitive Equations in spherical coordinates discretized on an Arakawa C-grid with the hydrostatic, Boussinesq and non-divergent flow assumptions among a few others. The linearized free-surface formulation (Roullet and Madec, 2000) is used. The vertical mixing is parameterized with a turbulent kinetic energy closure scheme (Blanke and Delecluse, 1993), improved by including a surface wave breaking parameterization (Mellor and Blumberg, 2004) and an energetically consistent

time and space discretization (Burchard 2002; Marsaleix et al. 2008). The convective processes are mimicked using an enhanced vertical diffusion parameterization (increasing vertical viscosity/diffusivity to $10 \text{ m}^2 \text{ s}^{-1}$ where static instability occurs). On the coarse (respectively fine) grid a harmonic isopycnal diffusion of 600 (100) $\text{m}^2 \text{ s}^{-1}$ and a biharmonic viscosity along geopotential surfaces of 12×10^{11} (8.5×10^9) $\text{m}^4 \text{ s}^{-1}$ are used. To keep a constant Reynolds grid number, the diffusive and viscous coefficients decrease from the equatorial nominal value (given just above) poleward and are respectively proportional to $\max[\Delta x, \Delta y]/\Delta_{max}$ and $\max[\Delta x, \Delta y]^3/\Delta_{max}^3$; Δx and Δy are the zonal and meridional grid spacing and Δ_{max} is the maximum of Δx and Δy taken over the whole ocean grid. The effect of mesoscale eddies on tracers relies on the Gent and McWilliams parameterization ($1000 \text{ m}^2 \text{ s}^{-1}$); it is used in the ORCA_REF and ERNA experiments (outside the nest only, where the resolution is $1/2^\circ$) while it is not activated in the ORCA_NOG one. A partial-slip sidewall boundary condition is used in momentum equations in all experiments; i.e. the tangential velocity at the coast is set to half the offshore velocity (Benshila et al., 2013). The discrete formulation used for the momentum advection term in the coarse grid is the vector form associated with an energy and enstrophy conserving scheme following the recommendation of Le Sommer et al. (2009) and Penduff et al. (2007) for the vorticity term, while in the fine grid the flux form is combined with an energy conserving scheme.

2.3. Experiments

Experiments start from rest and are initialised with the January Levitus et al. (1998) climatology. After a 3-year spinup using year 1989, they run

over 20-years (1990-2009) with interannual ERA-Interim atmospheric conditions derived from reanalysis. Turbulent fluxes are computed through CORE bulk formulae from Large and Yeager (2004), using ERA-Interim atmospheric state variables. Precipitations come from satellite products (Brodeau et al., 2010). ERA-Interim short and long wave radiative fluxes are reduced respectively by 3% and 6%, on large scales only, to better match GEWEX satellite observations in the latitude band $[40^{\circ}\text{S}-40^{\circ}\text{N}]$ (following the methodology of Large and Yeager (2008) for ISCCP products). Temperature and humidity state variables are also adjusted in high latitudes (north of 70°N) following the methodology detailed in Brodeau et al. (2010). To limit salinity drift that is partly due to precipitation uncertainties, a moderate Sea Surface Salinity (SSS) relaxation towards Levitus et al. (1998) monthly climatology is applied with a 60-day timescale over the upper 10 m. This relaxation is restricted to large scale oceanic structures selected by a Shapiro filter on SSS. In addition, a linear tapering of this relaxation is applied along continental shelves (from 0 at the coast to 1 400 km offshore), so almost no relaxation occurs in the Labrador and Irminger Seas.

3. Regional improvements

As a first step toward understanding the impact of model resolution on AMOC, we compare among simulations the circulation and hydrography in a few key regions of the Western North Atlantic current system. In the following, the time-mean characteristics if not specified, are computed over

199 1990-2009.

200 3.1. The Subtropical Gyre

201 Numerous studies contributed to explaining the Gulf Stream detachment
202 from the coast near Cape Hatteras (e.g. Spall, 1996). Notwithstanding,
203 modeling the Gulf Stream pathways remains a challenge in OGCMs even in
204 higher resolution configurations (Bryan et al. 2007; Chassignet and Garraffo
205 2001).

206 As done in previous studies (e.g. Coetlogon et al. (2006)), the position
207 of the Gulf Stream is identified and compared with observations using the
208 17°C isotherm near 177 m depth (Fig.2). Its climatological mean position
209 in ERNA shows a fairly good agreement with Levitus climatology, while
210 ORCA_REF simulates an excessively northward position downstream with
211 a Gulf Stream trapped along the continental rise. The latter is associ-
212 ated with the absence of the Northern Recirculation Gyre whose cyclonic
213 barotropic transport reaches 20 Sv in ERNA. Further east around 45°W, the
214 17°C isotherm in ERNA shows a northward loop that is associated with the
215 "Mann-Eddy". This pattern is not resolved in either the Levitus climatology
216 or in ORCA_REF and may be due to the insufficient resolution of both prod-
217 ucts (1° for observations, 1/2° for ORCA_REF) and, for the model output, to
218 erroneous reproduction of the circulation along the Grand Banks, in relation
219 with the North Atlantic pathways.

220 The amplitude of surface Eddy Kinetic Energy (EKE), averaged over the pe-
221 riod 1993-2009 and computed from five-days-mean outputs in ERNA, com-
222 pares well with observations (Ducet et al., 2000) and exceeds 1800 cm²s⁻²
223 (Fig. 3). The shape is slightly different but such a bias is common to oceanic

models at this resolution (Smith et al., 2000; Bryan et al., 2007). In ERNA, the 1200 cm^2s^{-2} contour is wider in the meridional direction to the west of 60°W and extends less to the east than observed, although the impact of New England seamounts near 61°W is in good agreement with observations (Ezer, 1994). The 1200 cm^2s^{-2} contour also reaches further upstream of Cape Hatteras along the Gulf Stream path in ERNA compared to observations, possibly due to an overly unstable simulated Gulf Stream related to the advection scheme used or/and to the lateral boundary condition. Note that the 50 cm^2s^{-2} EKE pattern related to the Azores current in ERNA is also in good agreement with observations. In ORCA_REF, EKE along the Gulf Stream pathway (not shown) is very weak (below 50 cm^2s^{-2}), which is primarily due to spatial resolution but also to the use of Gent and McWilliams parameterization (GM) (the experiment ORCA_NOG without GM reaches EKE levels of 100-150 cm^2s^{-2} in this area).

The vertical structure of the subtropical circulation along the western boundary is compared to repeated observations along Line W (courtesy of R. Curry, see Toole et al., 2011, their Fig.4; see Fig. 1 for the section location). ERNA shows a remarkable extension of the Gulf Stream core over the top 1000 m depth and a clear shift from the continental slope, as observed. The signature of southward flowing DWBC is visible at depth, albeit with smaller amplitude than observed. In ORCA_REF, the Gulf Stream core is excessively diffuse and does not penetrate deeper than 500 m and the DWBC core is clearly missing. Observations (e.g. Bower and Hunt, 2000) revealed interactions between the

upper ocean circulation near the Gulf Stream and circulation at depth in DWBC. Using model experiments, Zhang and Vallis (2007) invoked bottom vortex stretching as the mechanism that explains the Gulf Stream position off the continental slope downstream of Cape Hatteras and suggested that the intensified DWBC plays a role in the Northern Recirculation Gyre onset. It is not among our objectives to revisit these results. Still, based on the numerous sensitivity experiments that we ran and the diagnostics of the intensity of bottom vortex stretching, we confirm that the improvement of both Gulf Stream and DWBC pathways in ERNA compared to ORCA_REF is not fortuitous.

3.2. The Intergyre region

The North Atlantic Inter-Gyre region is the transition between the subtropical and the subpolar gyres (Marshall et al., 2001), extending from the Grand Banks tail up to the North West Corner (NWC), from the western boundary to the east of the Mid-Atlantic Ridge. Sea Surface Height observations show that downstream of Cape Hatteras, around 45°W - 44°N , the Gulf Stream current splits in two branches: one flows to the northeast Atlantic basin via the North Atlantic Current (NAC hereafter) through the NWC, and one joins the Worthington Gyre and the Azores current to the southeast (Fig. 5a). Such a bifurcation is well reproduced in ERNA where three troughs are clearly visible in the NAC pathways at 40°N , 44°N and 47°N , which is in very good agreement with observations (Fig. 5b). The NAC northward extension in the NWC is also well reproduced in ERNA, as we can see on the velocities structures at the surface

(Fig 6a). The eastward, almost zonal extension of the NAC centered around 50°N above the Mid-Atlantic Ridge is not as zonal in ERNA as observed, suggesting that the simulated subpolar gyre has an underestimated eastward extension. The NAC meandering structure is also visible in the EKE field, both in observations and ERNA with local maxima off the Grand Banks (Fig. 3).

The difference between ERNA and ORCA_REF is large in this region; in ORCA_REF the NAC flows further offshore, from the southeast of the Grand Banks to the Iceland basin without meandering off the Flemish Cap or forming a NWC (Fig. 5c, 6a and 6b). Hence the NAC moves to the northeast too far south of the Charlie Gibbs Fracture Zone which is associated with an overestimated southward extension of the subpolar gyre.

The NAC position strongly impacts thermohaline properties in the Inter-gyre region (Fig. 7). In ORCA_REF, the Sea Surface Temperature (SST) and the Sea Surface Salinity (SSS) exhibit large cold and fresh biases (Fig. 7b, d). Although these biases partly derive from a mismatch in scales between the simulation and climatology (which has an even coarser resolution), they are common to ocean models (Griffies et al., 2009), and hence to climate models. Weese and Bryan (2006) have shown, using a coupled model, that reducing those biases has a positive impact on the atmosphere and also suggests a potential impact on water masses at higher latitudes. These biases do not exist at all in ERNA, where surface anomalies are rather warm and salty (Fig. 7a,c). Temperature and salinity anomalies related to the wrong position of the NAC in ORCA_REF are also visible at depth, down to approximately 1000 m. By contrast, the thermohaline profile in ERNA com-

puted offshore of the Flemish cap (not shown) compares well with observed
climatology.

The vertical structure of the current along the Grand Banks is compared
to observations (Schott et al. (2006), their Fig.1b) at 43°N; see Fig.1 for
section location). ERNA (Fig. 8a) shows a position and extension at depth
(down to the bottom) that compares well with observations. The ERNA
NAC mean intensity of 55 Sv is weaker by at least a factor of 2 compared
to the evaluation by Schott et al. (2006) of 142 Sv, but is comparable to
that obtained by Bryan et al. (2007) in their 1/10° model. In ORCA_REF
(Fig. 8b), as already noticed for the Gulf Stream, the NAC surface currents
are much slower and cover a wider area. The DWBC vertical extension is
limited to 2900 m depth only and does not show an intensification along the
topographic slope as in ERNA. As will be discussed later, the main pathway
of DWBC is indeed located to the west of Mid-Atlantic Ridge (Fig. 6d),
which is not covered by the section in Fig. 8.

3.3. The Subpolar Gyre

In the Subpolar Gyre, heat carried from the subtropics by the NAC, the
upper part of AMOC, is released to the atmosphere as intermediate and
dense water is formed. This water incorporates into the DWBC, together
with denser water masses overflowing through the sills between Greenland
and Scotland (Dickson and Brown, 1994). The DWBC, which is the deep
limb of AMOC, merges with the deep barotropic Subpolar Gyre in this re-
gion. Hence intercomparing the simulated Subpolar Gyre characteristics is

relevant to our objective of understanding how model resolution affects the AMOC.

The Sea Surface Height structure and amplitude in the ERNA Subpolar Gyre are close to observations (Fig. 5a,b), in particular the extension of low sea level along Newfoundland down to the Grand Banks. In ORCA_REF, the Sea Surface Height structure is marked by its excessive southward extension due to the misrepresentation of NAC and NWC (Fig. 5c).

The maximum mean barotropic streamfunction ψ_{max} (not shown), measured in a box centered in Labrador Sea [55°W-53°W and 56.5°N-58.5°N], is 36 Sv and 31 Sv in ERNA and ORCA_REF respectively. When considering the convective years of the mid 1990s only, the annual mean maximum in ERNA is in the range [43-45] Sv which is close to the 43 Sv reference value obtained in Treguier et al. (2005) for a set of high resolution simulations [1/6° - 1/12°], while in ORCA_REF it remains at 34 Sv. In the Irminger Sea box [42°W-38°W and 59°N-61°N], ψ_{max} is 35 Sv in ERNA which is, again, comparable to the simulations of Treguier et al. (2005), while ORCA_REF reaches only 30 Sv.

To further analyse the structure of currents in the Labrador Sea, we compared both experiments with repeated observations along the AR7W section (Fig. 9; see Fig. 1 for section location). The West Greenland Current, visible at the northern end of the AR7W section and the Labrador Current at the southern end flow cyclonically around the Labrador Sea. In ERNA, the barotropic structure of currents matches quite well that of the composite of Hall et al. (2013) (see their Fig 5a). Remarkable features arise in ERNA with anticyclonic recirculation cells offshore of both boundary currents, which

349 have already been described in observations (Lavender et al., 2000; Hall et al.,
 350 2013). Note also that the West Greenland Current is tilted offshore at depth
 351 as found in observations, although the simulated tilt is underestimated. This
 352 is presumably due to the underestimation of the Denmark Strait Overflow
 353 Water in ERNA, which is also visible in the deep Labrador Current, a bias
 354 that is common to OGCM even at higher resolution (Treguier et al., 2005). In
 355 ORCA_REF, the boundary currents are weaker and broader than in ERNA
 356 and the interior recirculation cell is hardly visible.

357 Convective activity in the Labrador Sea, as illustrated by the winter (February-
 358 April) mixed layer depth (MLD), differs significantly between experiments
 359 with a deeper mixed layer over a larger area in ERNA than in ORCA_REF
 360 (Fig. 10, based on the 0.03 kg m^{-3} density criteria). In ERNA, contrary to
 361 ORCA_REF, deep winter mixed layers develop also in the narrow Labrador
 362 Current, consistent with observations of upper Labrador Sea Water forma-
 363 tion (Pickart et al., 1997) and another high resolution model (Deshayes et al.,
 364 2007). Note that the presence of subtropical warm waters in the NWC con-
 365 tributes to limiting the southward extension of the negative convective patch
 366 in ERNA.

367 In the Irminger Sea, the mean winter MLD reaches 800 m depth to the south-
 368 east of Greenland in ERNA, a pattern apparently linked to the Labrador
 369 Sea convective patch which does not exist in ORCA_REF. Convection in the
 370 Irminger Sea is consistent with observations (Vage et al., 2011a, 2008; Pickart
 371 et al., 2003) and other simulations (Deshayes et al., 2007).

372 The climatology of observed winter MLD (de Boyer Montégut, 2004), up-
 373 dated to include ARGO float data to September 2008 on a $2^\circ \times 2^\circ$ grid resolu-

tion) shows values hardly deeper than 400 m depth in the central Labrador Sea, suggesting that both simulations largely overestimate the mixed layer depth (it exceeds 2400 m and 1600 m in ERNA and ORCA_REF respectively).

It should be kept in mind that simulated mean values cover the period 1990-2009, different to the period of observation used for the climatology data (essentially ARGO data from 1995 to 2008). Still, it must be noted that winter MLD is overestimated in ERNA and ORCA_REF, a bias common to ocean hindcasts using NEMO (Rattan et al., 2010).

Although the winter mean MLD (Fig. 10a, b) over the period 1990-2009 seems lower in ORCA_REF than in ERNA, a monthly time series (not shown) of MLD, averaged in a box located in the central Labrador Sea, shows that this statement depends effectively on the period considered. During strong convective events in the early 1990s, the MLD is of the same order of magnitude in both experiments reaching deeper than 2500 m. It is only in late the 1990s that the MLD is significantly lower in ORCA_REF than in ERNA. Our interpretation is that the spatial resolution in ERNA is not sufficient to reproduce the mesoscale restratification processes parameterized with GM in ORCA_REF. An additional low-resolution experiment (ORCA_NOG) without GM parameterization has been performed over the same period to illustrate the impact of GM on convection. The winter mean MLD is very similar in amplitude to ERNA, but it differs in shape (Fig. 10c). Hence spatial resolution in ERNA hardly affects the spatial structure of the convective patch in the subpolar gyre, despite at least partially resolving the mesoscale activity. Mesoscale restratification processes can be indirectly evaluated via

surface EKE. In ERNA, local maximum ($80 \text{ cm}^2\text{s}^{-2}$ contour) arises north of 60°N and extends to the northwest along the Western Greenland Current (Fig. 11b). This pattern corresponds to a relatively shallower mixed layer (Fig. 10a). In observations it is shifted westward around 52°W and extends to the south. This structure is associated with eddies known as Irminger rings, which are important for restratification in the interior Labrador Sea (Chanut et al., 2008). Their mis-representation in ERNA largely contributes to the overestimated winter MLD. Irminger rings are related to a topographic feature near Cape Desolation with very close isobaths on the cross-shore direction (Katsman et al., 2004; Eden and Böning, 2002) which seems to require a representation of the bathymetry with an even higher resolution than the one of ERNA. Note that AVISO observations are not able to capture EKE activity beneath the sea-ice cover near the coast around the Irminger and Labrador Seas, so it is not possible to evaluate EKE local maxima in the coastal strip simulated in ERNA.

3.4. The Nordic Seas

Similarly to the subpolar gyre, the Nordic Seas receive heat from the subtropics via the NAC and release it to the atmosphere as dense water is formed. They are also the source region for water masses overflowing the Greenland-Scotland ridge, which constitute the densest components of the DWBC. Spatial resolution seems to affect both processes, convection and overflow.

As found in the Labrador Sea, the mean winter mixed layer depth is substantially deeper in ERNA compared to ORCA_REF and, again, exceeds

424 observed climatology (Fig. 12). Nevertheless, the spatial structure of the
425 convective patch is clearly more realistic in ERNA, centered around 75°N,
426 0°E, while it is located along the Norwegian coast in ORCA_REF. Simulation
427 ORCA_NOG produces a mean winter MLD very similar to ORCA_REF, sug-
428 gesting that convective processes are not well developed in both experiments
429 in this area. As a result, it is likely that the location of the convective patch
430 is improved in ERNA because the circulation and thermohaline properties
431 are overall more realistic.

432 This notwithstanding, in ERNA the East Greenland Current is narrower and
433 stronger than in ORCA_REF (observations are not available to make a direct
434 comparison). This reduces the offshore extension of sea-ice, in particular in
435 summer, which, in turn, induces large SST (up to 1°C) and SSS (up to 1
436 PSU) anomalies near the sea-ice edge as the ocean fraction that is free of ice
437 is directly exposed to radiative and turbulent fluxes. These anomalies are
438 then progressively advected southward toward the Irminger and Labrador
439 Seas where they contribute to a large-scale warm and salty bias. Hence, the
440 increase in resolution in the Nordic Seas has both positive (the improvement
441 of convection location) and negative (warm and salty bias in the subpolar
442 gyre) consequences.

443 Evaluating the simulated Nordic Seas in detail is beyond the scope of this
444 paper. Still, we speculate here what we describe in the next section, namely
445 that the improvement of Nordic Seas dense water formation is consistent
446 with the improvement of dense water overflow through the Denmark Strait
447 in ERNA.

448

4. Impacts on the AMOC

The Atlantic Meridional Overturning Circulation (AMOC) is a synthetic representation of the large-scale northward surface flow of warm and salty water and the deep southward return flow of cold and fresh water. In the following we analyse how regional improvements related to the 1/8° nest impact the AMOC in underlining the role of dense water transported by the DWBC from the overflows downstream to mid-latitude. We follow on with a detailed analysis of the latitude dependence of the AMOC maximum, in both density and depth coordinates, to infer the upper ocean influence on the AMOC. Finally, we discuss and compare our findings with observations of the AMOC structure at 26.5°N, near the southern boundary of the nest.

4.1. Meridional overturning streamfunction

We choose to represent the AMOC in σ_2 density space (Fig. 13) because it reveals the contribution of newly formed dense water masses better than the classical depth space AMOC. We ensured that the initial three-year spinup, although short, does not influence the following results through the maximum AMOC at 43°N time series (not shown).

The temporal mean AMOC maximum arises at high latitude close to the North Atlantic convective areas and reaches 24 Sv at 54°N and 17 Sv at 58°N in ERNA and ORCA_REF respectively. A second local AMOC maximum arises to the south in both experiments revealing again a 7 Sv difference between ERNA and ORCA_REF. These secondary maxima are located at the same latitude and have the same amplitude, namely 21 Sv and 14 Sv for ERNA and ORCA_REF respectively, as the AMOC maxima when calculated

in depth space (not shown). This is consistent with previous studies comparing the AMOC in depth and density space (Danabasoglu et al., 2013; Zhang, 2010; Griffies et al., 2009), advocating the use of the latter representation for high latitudes AMOC investigations.

In ERNA the AMOC maximum is located in density layers close to 36.78 kg m^{-3} at high latitude and 36.62 kg m^{-3} for the second maximum, while in ORCA_REF it is close to 36.52 kg m^{-3} at high latitude and 36.39 kg m^{-3} to the south. Hence water masses forming the deep limb of the AMOC are overall denser in ERNA than in ORCA_REF. This also suggests that these water masses tend to become lighter from 55°N southward. This is clearly visible in ERNA, where the overturning streamfunction contours for densities of $36.7\text{-}36.85 \text{ kg m}^{-3}$ are oriented towards lower density at low latitude. Such trend is not obvious in ORCA_REF, where overturning streamfunction contours in the deep limb of AMOC are either flat or bending towards higher density at low latitude. The latter remains unexplained, although it seems to be a feature common to other ORCA $1/2^\circ$ simulations (Biaostoch et al. 2008, their figure 1d).

In summary, the contrast in shape and intensity of the AMOC between both experiments is important. Here an increase in horizontal resolution results in a 7 Sv stronger AMOC. It also improves the circulation at the bottom, with a clearly defined deep AMOC limb. The question is where these differences come from, i.e. whether: an increased horizontal resolution is amplifying existing processes or whether there are new processes being represented ? We focus firstly on the deep limb of the AMOC, i.e. dense

498 water transport by the DWBC, to answer this question.

499

500 *4.2. Deep Western Boundary Current*

501 The DWBC constitutes the AMOC deep limb exporting NADW equa-
 502 torward (see Lozier 2012 for a review on AMOC). We hereafter analyse the
 503 DWBC transport and whenever possible compare it with direct observations
 504 along its pathways from the Denmark strait overflow down to Cape Hatteras.
 505 The total transport in the DWBC is computed for water masses denser than
 506 27.68 kg m^{-3} . We also compute the transport of water masses denser than
 507 27.80 kg m^{-3} that characterizes the North East Atlantic Deep Water and
 508 the Denmark Strait Overflow Water masses. All transport calculations are
 509 bound onshore by topography and offshore by zero isotach.
 510 We chose seven sections to monitor dense water transport in the DWBC: at
 511 its origin at the Denmark strait (section DSO), in the Irminger sea (sections
 512 IRM, upstream of the local convection site, and GRE near Cape Farewell),
 513 in the Labrador Sea (the south-western part of AR7, and section FIS studied
 514 by Fischer et al. 2010), near Grand Banks (section SCH studied by Schott
 515 et al. 2006) and finally near Cape Hatteras (section LIW along line W,
 516 <http://www.whoi.edu/science/PO/linew/index.htm>).

517

518 The DWBC total transport (Fig. 14a) and transport for densities greater
 519 than 27.80 kg m^{-3} (Fig. 14b) are systematically larger in ERNA than in
 520 ORCA_REF. They increase gradually from the Denmark strait down to the
 521 central Labrador Sea, then substantially decrease in the Inter-gyre region
 522 through FIS and SCH sections, and finally, in ERNA only, intensify again

in the Northern Recirculation Gyre. In ORCA_REF, the DWBC transports at sections SCH and LIW almost vanish, as also indicated by cross-section velocities (Fig. 8b, 4c). As a result, both simulations differ in the intensity of DWBC transport, but also in their DWBC pathways through the Inter-gyre region. Below, we investigate each section in detail, contrasting both simulations and comparing them with observations.

At the Denmark strait, the dense DWBC transport (of water denser than 27.80 kg m^{-3}) is very close to observations in ERNA and 30% higher than in ORCA_REF, the difference reaching almost 1 Sv. The transport of water denser than 27.88 kg m^{-3} reaches 2.4 Sv in ERNA against 1.3 Sv in ORCA_REF, which represents 75% and 54% of the dense transport (of water denser than 27.80 kg m^{-3}) respectively. This suggests that water masses near sill depth are denser in ERNA than in ORCA_REF. Ultimately, the 27.80 kg m^{-3} isopycnal surface in GIN Seas (at about 100m depth) occupies a larger horizontal area and is located shallower in ERNA than in ORCA_REF, which facilitates the formation of denser water masses by convection.

Downstream of the Denmark Strait through the IRM section the total transport significantly increases in both experiments, reaching almost the same intensity. The dense DWBC transport is strongly reduced in ORCA_REF while it increases in ERNA due to the better resolved entrainment and to the presence of denser water at the Denmark Strait compared to ORCA_REF. We have noted the absence of North East Atlantic Deep Water flowing northward on the western flank of the Reykjanes Ridge in ERNA,

548 which increases the relative contribution of Denmark Strait Overflow Waters
549 in the DWBC, a clear bias in ERNA. The entrainment process is not per-
550 fectly resolved in ERNA either as there is no water denser than 27.88 kg m^{-3}
551 in the subpolar gyre, which is contrary to observations.

552

553 The total and dense water transports increase from IRM to GRE in both
554 simulations, although to a larger extent in ERNA than in ORCA_REF.
555 This reflects the contribution of the Irminger Gyre (Vage et al., 2011a). In
556 addition, in ERNA there is a clear export of LSW from the Labrador Sea to
557 the Irminger Sea which then returns to the DWBC, consistent with observa-
558 tions (Lavender et al., 2000), which is not visible in ORCA_REF. Moreover,
559 convection occurs in the Irminger Sea in ERNA (Fig. 10a) and forms water
560 masses denser than 27.74 kg m^{-3} in the 1990s, which contributes to an in-
561 crease in the dense transport through GRE.

562

563 The total DWBC transport is analysed in both experiments through sec-
564 tion AR7. The simulated value in ERNA is very close to observations by
565 Hall et al. (2013). In ORCA_REF it is 33% smaller; this is to be attributed
566 to a weaker transport upstream as described before, a lower level of dense
567 water formation in the Labrador Sea, and also to the missing recirculation
568 in the interior Labrador Sea (Lavender et al., 2000) that feeds back into the
569 Labrador Current (Fig. 9). The dense transport is also much larger in ERNA
570 than in ORCA_REF, because (i) the currents are stronger at depth in ERNA
571 (Fig. 9 b), and (ii) 27.80 isopycnal is shallower in ERNA (around 1000 m
572 depth) than in ORCA_REF (around 2500 m depth, blue contours in Fig. 9c).

573 The latter is due to convection in ERNA that produces water masses denser
574 than 27.80 kg m^{-3} , which is clearly unrealistic. As a result, dense transport
575 in ERNA is larger than the observations.

576

577 Observations across section FIS (Fischer et al., 2010) yield similar total
578 transport but larger dense transport than through AR7 (Hall et al., 2013).
579 As at AR7, total and dense water transports in ERNA compares well with
580 FIS observations, while both transports are smaller in ORCA_REF.

581

582 Near the Grand Banks, in both experiments the SCH section shows the
583 first strong reduction in total DWBC transport, although already initiated
584 at the FIS section. This region is a key location for interaction between the
585 DWBC and the NAC in ERNA, as suggested by observations (Bower et al.,
586 2011; Kieke et al., 2009), with the circulation of upper Labrador Sea Wa-
587 ter eastward along with the NAC downstream of Flemish Cap. Although
588 both experiments show an important decrease in the DWBC transports, it
589 is dramatic in ORCA_REF as there is no dense transport through SCH and
590 hardly any total transport. Indeed, the main pathway for the DWBC in
591 ORCA_REF is eastward at the exit of the subpolar gyre and then southward
592 on both sides of the Mid-Atlantic Ridge, as found in the simulation described
593 by Deshayes et al. (2007) (see Fig. 6d). In ORCA_REF, there is no interior
594 pathway as described by Bower et al. (2009) and associated with a strong
595 eddy activity eastward of the continental shelf between 40°N and 50°N . The
596 pathway along the Mid-Atlantic-Ridge arises in ERNA (Fig. 6c), but it is
597 clearly of minor importance (similar as observations by Kieke et al. 2009), as

the DWBC transport across section SCH is close to the AMOC strength at this latitude (20 Sv in density coordinates, and 17 Sv in depth coordinates). It also compares very well with observations, both for the total and for dense transport.

Observations of the circulation across Line W, located north of Cape Hatteras, exhibit the signature of the Northern Recirculation Gyre along with the DWBC at depth (Toole et al., 2011). As noted above, the Northern Recirculation Gyre does not exist in ORCA_REF, but it is well represented in ERNA (Fig. 4b). Accordingly, total and dense transport in ERNA compare well with observations, while there is hardly any southward transport through section LIW in ORCA_REF. Note that ERNA transports are actually overestimated, probably due to exaggerated recirculations along the DWBC within the Northern Recirculation Gyre.

In summary, the ERNA experiment is clearly different from ORCA_REF with a stronger DWBC representation all along the western boundary of the North Atlantic. At high latitudes the DWBC transport in ERNA increases gradually from the Denmark Strait, through entrainment downstream in the Irminger Sea and due to the convective process in both the Labrador and Irminger seas. All three processes are poorly simulated in ORCA_REF. In addition, recirculations along DWBC (in the Labrador Sea and the Northern Recirculation Gyre), well reproduced in ERNA only, strengthen the transports (in fact excessively so in the Northern Recirculation Gyre), which contributes to improving the comparison with observations. Finally, there is a

clear bias in the pathway of the DWBC in the ORCA_REF Inter-gyre region,
which affects all comparisons with observations further south of this region.
As a result, DWBC transports in ERNA are comparable to observations,
while transports in ORCA_REF are much smaller and even null south of
Flemish Cap.

4.3. Upper ocean influence on the AMOC

When computing the AMOC in density coordinates ($\text{AMOC}-\sigma$), it is relatively straightforward to relate the DWBC transport with AMOC intensity. By contrast, the AMOC intensity in depth coordinates ($\text{AMOC}-z$) can not be directly related to the DWBC transport because of compensations in the horizontal that are actually indicative of the influence of upper ocean circulation on the AMOC. We explore both perspectives by investigating the latitudinal dependence of AMOC maximum, first in density and then in depth coordinates.

According to the DWBC transport in ERNA, the $\text{AMOC}-\sigma$ increases gradually southward from 5-6 Sv at 68°N (north of the Denmark Strait overflow), up to 24 Sv at 52°N (Fig. 15, black dashed line). This increase is due to entrainment and convective processes, as recirculations along DWBC do not contribute to intensify the AMOC (they nearly cancel out when averaging zonally). The AMOC maximum then decreases in the latitude band 52° - 42°N (vertical yellow stripe) which corresponds to the Inter-gyre region, suggesting intensified mixing in this latitude band, with lighter subtropical water masses transported by NAC. It finally stabilizes around 22 Sv at 35°N ,

the secondary maximum of the overturning streamfunction (Fig. 13).

The picture emerging from ORCA_REF is very similar (Fig.15, red dashed line), except that each process strengthening AMOC is hindered, as has already been noted for DWBC transports. On the other hand, the decrease in AMOC in the Intergyre region is more important in ORCA_REF than in ERNA. This suggests that along its peculiar path east of Flemish Cap, NADW experiences more diapycnal mixing with surrounding lighter water masses. Actually, the cumulated southward transport of dense water masses from Flemish Cap eastward reveals that most of the AMOC deep limb is located on both sides of the Mid-Atlantic Ridge (not shown). This considerably lengthens the pathway of NADW from the Labrador Sea southward, hence increasing the amount of diapycnal mixing undergone along the route. Indeed, we observe a deepening of the isopycnal surface $\sigma_2=36.925 \text{ kg m}^{-3}$ (at a mean rate of $[10-20] \text{ m year}^{-1}$) throughout the simulation, with the largest amplitude to the west of the Mid-Atlantic Ridge, in the latitude band that corresponds to the AMOC decrease (purple and yellow stripes), which corresponds to the mean pathway of the DWBC in ORCA_REF.

In calculations of the AMOC in depth coordinates, only one maximum appears at about 35°N in both simulations (Fig. 15, plain lines), as most of the (dense) southward flow in the subpolar gyre is compensated for by a (lighter) northward flow at the same depth. The latitudinal dependence of the AMOC maximum differs a lot among simulations. In ORCA_REF, the AMOC maximum increases almost linearly from the overflows (vertical

673 cyan stripe) to 35°N, reflecting both (i) the deepening of DWBC (as revealed
 674 by the overturning streamfunction in depth coordinates, not shown), and (ii)
 675 the uplifting of the penetration depth of the gyre circulation (from barotropic
 676 in the subpolar gyre to baroclinic in the subtropical gyre). By contrast, in
 677 ERNA there are two sharp increases in AMOC: at the latitudes of Flem-
 678 ish Cap (vertical yellow stripe) and Cape Hatteras (vertical pink stripe),
 679 where there are major interactions between the upper ocean circulation and
 680 the DWBC. At higher latitudes, the very close depth-coordinates AMOC
 681 in ERNA and ORCA_REF, despite the substantial difference in AMOC- σ ,
 682 is consistent with previous studies (Danabasoglu et al., 2013; Zhang, 2010;
 683 Griffies et al., 2009) which support the claim that AMOC-z is not the proper
 684 way to investigate the NADW fraction associated with deep water formation.

685
 686 At 35°N, AMOC-z and AMOC- σ have similar values (22 Sv in ERNA and
 687 14 Sv in ORCA_REF). These are 2 Sv in ERNA and 4 Sv in ORCA_REF
 688 smaller than the maximum AMOC- σ at higher latitude. Hence the differ-
 689 ence between σ - and z- AMOC maxima is the smallest in ERNA, in which
 690 the NAC and the Gulf Stream interact with the DWBC. This suggests that
 691 the NADW formation rate alone does not set the amplitude of AMOC at
 692 mid-latitude, as the interaction with the upper ocean circulation plays a role
 693 as well.

694
 695 South of 35°N, AMOC- σ and AMOC-z have similar values which are rel-
 696 atively stable in ORCA_REF while they decrease continuously in ERNA,
 697 suggesting that both upwelling and diapycnal mixing are very active in the

698 northern part of the subtropical gyre in ERNA.

699

700 4.4. AMOC at the RAPID section

701 Continuous observations along the RAPID section yield an unprecedented
 702 direct monitoring of the AMOC strength at 26.5°N. The AMOC amplitude
 703 in ERNA, which is 18 Sv at this latitude, compares well with 17.3 Sv from
 704 observations (<http://www.noc.soton.ac.uk/rapidmoc/>), although the depth-
 705 cumulated transport differs in the deep AMOC limb, the thickness of the
 706 simulated one being underestimated (Fig. 16a). Such a bias also exists in
 707 ORCA_REF, which in addition has a weak AMOC amplitude (about 13 Sv).
 708 It is important to keep in mind that interannual variability in AMOC is sub-
 709 stantial, based on observations (Cunningham et al., 2007) as well as modeling
 710 experiments (Biaostoch et al., 2008), hence comparing AMOC amplitude aver-
 711 aged over different time periods (2004-2011 for RAPID data vs 1990-2009 for
 712 model simulations) may lead to significant differences. However, interannual
 713 variability cannot explain the large difference in AMOC strength between
 714 ERNA and ORCA_REF, associated with a 250 m shallower AMOC maxi-
 715 mum depth in ERNA.

716

717 Finally, we compare the two simulated density structures at this latitude
 718 (Fig. 16b), averaged over the whole basin (blue line) and along the west-
 719 ern boundary (85°W-70°W, black line). Two patterns clearly emerge above
 720 and beneath 900 m depth. From 900 m down to 3000 m depth, ERNA
 721 is denser than ORCA_REF. This is particularly the case along the western
 722 boundary, suggesting a primary contribution from the NADW transported

by the DWBC. Between 300 m and 900 m depth, ERNA is lighter than ORCA_REF along the western boundary, but this difference almost disappears when averaging it over the whole section, indicating that ERNA is denser than ORCA_REF in the eastern part of the basin. Both effects can be seen as changes in the thermocline depth (confirmed by temperature and salinity differences over the section, not shown) that is deeper to the west and shallower to the east of the basin in ERNA compared to ORCA_REF. It is expected that increasing spatial resolution intensifies horizontal fronts, but how this would project onto thermocline depth remains unclear. At the eastern part of the basin, thermocline uplifting is also due to a better representation of the Mediterranean overflow in ERNA (vertical sections not shown).

5. Discussions

This study shows how an increase in the resolution significantly impacts the North Atlantic circulation at surface and at depth. We now discuss these improvements and their impact on AMOC as it remains difficult, even at 1/80 resolution, to represent some processes.

5.1. Bathymetry and numerics

The horizontal resolution increase is a major difference between the ORCA_REF and ERNA experiments, together with a few numerical changes. This increase allows the model to better reproduce the topographic constraint on currents that flow, for instance, over the continental rise as the DWBC. The topography impacts the behavior of currents in key regions such as the Grand

747 Banks where the NAC and the DWBC cross, or off the Southwest Green-
748 land coast where abrupt topographic changes contribute to the generation of
749 eddies (Katsman et al., 2004). In addition, we also point out that improve-
750 ments in the representation of boundary currents are related to numerical
751 choices such as horizontal viscosity and momentum advection scheme which
752 are known to impact dynamics in the North Atlantic.

754 5.2. DWBC assessment

755 In order to assess the impact of improved western boundary current sys-
756 tems on the AMOC, we compare the transport in the DWBC through a few
757 sections in ERNA, ORCA_REF and from observations. We acknowledge that
758 we compare, in Fig.14, the simulated DWBC transport averaged over 1990-
759 2009 with sparse and irregularly sampled observations. However, we are
760 restricting the simulated mean values over the same years as observations
761 does not significantly change the result. In particular, the transport of the
762 densest water masses ($\sigma_0 > 27.8 \text{ kg m}^{-3}$) through the AR7 south-west end
763 section is overestimated. This is due to an excessive transformation of sur-
764 face water masses in the Labrador Sea similar to that detailed in Gulev et al.
765 (2007). Those overly dense water masses formed in the Labrador Sea replace
766 both the missing Denmark Strait Overflow Water and the Iceland Scotland
767 Overflow Water in ERNA; this explains why the total DWBC transport in
768 ERNA is close to observations. The DWBC transport in ERNA is then im-
769 proved for incorrect reasons; we are currently investigating whether and how
770 this affects the mechanisms of AMOC variability in ERNA.

771

772 5.3. *Overflows*

773 Not surprisingly for a vertical Z-level model, overflows are not well re-
 774 solved either in ERNA or in ORCA_REF. Nevertheless, dense water trans-
 775 port ($\sigma_0 > 27.80 \text{ kg m}^{-3}$) through the Denmark strait in ERNA is closer to
 776 observations than in ORCA_REF (Fig.14). A section showing normal veloc-
 777 ities and isopycnals (not shown) reveals that this improvement is related to
 778 stronger southward currents as well as the presence of denser water masses in
 779 the range $[\sigma_0 > 27.80 \text{ and } 27.88] \text{ kg m}^{-3}$. We show that convective activity
 780 has been enhanced in the Nordic Seas in ERNA compared to ORCA_REF,
 781 which increases dense water production in this density range.

782 5.4. *NAC short-cut*

783 From ORCA_REF to ERNA, the NAC circulation off Newfoundland has
 784 clearly improved, leading to more realistic water mass characteristics in the
 785 intergyre region at the surface (Fig.7a,b) and at depth. Nevertheless, it is
 786 also worth noting the existence of a NAC short-cut on the southeast side
 787 of the Subpolar Gyre that directly feeds the Irminger current with warm
 788 and salty water advected from the Subtropical Gyre. This feature and its
 789 baroclinic destabilization likely explain the overestimated EKE (exceeding
 790 $80 \text{ cm}^2 \text{ s}^{-2}$ seen in Fig.11). It occupies a large area in the southeastern part
 791 of the Irminger Sea. This pattern, which also appeared in 1/12° NEMO re-
 792 gional configurations (see Dussin and Treguier (2010), their Fig.1), develops
 793 rapidly after the beginning of the simulation (within a few years). We hy-
 794 pothesize that this pattern is a consequence of existing biases in water masses
 795 leading to a weaker vertical density gradient in the eastward flow (from the
 796 northwest corner). It then becomes more barotropic and thus more sensitive

797 to the Reykjanes ridge tail topography which constrains the flow to follow
798 planetary potential vorticity contours, oriented meridionally in this area. This
799 idea is supported by numerical experiments in Zhu et al. (2010) (their Fig.9):
800 the NAC short-cut does not exist in a simulation using full spectral nudging
801 on temperature and salinity while it appears when relaxing this forcing. As
802 a consequence of this short-cut in ERNA, temperature and salinity biases
803 (Fig.7a,c) remain in the North Atlantic at surface and at depth. Biases are
804 even amplified very locally off the Greenland and the Labrador coasts with
805 respect to ORCA_REF.

806 The salinization bias in particular is common to numerous configurations
807 as illustrated by Treguier et al. (2005) when analysing four high resolution
808 model spanning $[1/6^\circ - 1/12^\circ]$. They suggest an advective origin and rule
809 out surface forcing and vertical mixing which differed between models. Rat-
810 tan et al. (2010) go further, emphasizing that the initial central Labrador
811 Sea salinity drift (lasting for 10 years) is linked to misrepresented freshwa-
812 ter pathways on both sides of Greenland, and to overestimated transport of
813 warm and salty water by the Irminger current. We found the same drift
814 and adjustment time period in both ERNA and ORCA_REF, using either
815 inter-annual or a repeated normal year forcing. Interestingly, following the
816 suggestion of Rattan et al. (2010), we apply a very weak SSS restoring within
817 a 400 km wide band offshore (so almost no salinity restoring is applied in the
818 Subpolar Gyre) to avoid spurious weak Eastern Greenland Current freshwa-
819 ter transport, but it has no clear impact on this salinity drift either in ERNA
820 or ORCA_REF.

821

822 5.5. *Deep intergyre circulation*

823 The Intergyre surface circulation differs drastically between ERNA and
 824 ORCA_REF; this is also the case at depth. Indeed, in ORCA_REF almost
 825 all DWBC transport exiting the Labrador Sea is exported eastward from
 826 Flemish Cap. One fraction flows through the Charlie Gibbs Fracture Zone
 827 and then recirculates in the Subpolar Gyre, while the rest flows southward
 828 along both sides of the Mid-Atlantic Ridge. Observations reported in Kieke
 829 et al. (2009) suggest that such an interior pathway exists for NADW, but
 830 that the main southward core of NADW remains along the continental shelf
 831 in the intergyre region. In ORCA_REF, the interior pathway is predominant
 832 and almost no NADW flows across the SCH section. Spence et al. (2012)
 833 suggest that coarse resolution models (1°) using high viscosity values have
 834 difficulties representing interior pathways for NADW towards low latitudes.
 835 Perhaps because it employs relatively low viscosity, ORCA_REF is not af-
 836 fected by this issue. In ERNA, both pathways are visible but the DWBC
 837 path along the western continental shelf is, by far, predominant, in agree-
 838 ment with observations.

840 5.6. *Model-dependency of the results*

841 Increasing the horizontal resolution over the North Atlantic from $1/2^\circ$
 842 to $1/8^\circ$ leads to a strong intensification of the time mean AMOC maximum
 843 in our experiments. It is noteworthy that this result contrasts with the
 844 one obtained by Hodson and Sutton (2012). Indeed, when using two cou-
 845 pled AOGCM with oceanic resolution 1° and $1/3^\circ$, the time mean maximum
 846 AMOC intensities (over 70 years of integration) were 22 Sv and 20 Sv at

847 Cape Hatteras respectively. Hence the AMOC of their 1° ocean presents a
 848 higher intensity than the $1/2^\circ$ ORCA_REF (whose average is only 14 Sv and
 849 endures a weakening trend over 20 years), while their $1/3^\circ$ has a value of
 850 the same order as ERNA $1/8^\circ$. In Hodson and Sutton (2012), AMOC mag-
 851 nitudes arise concurrently with an overestimation (by nearly a factor 2 in
 852 the 1° ocean configuration) of mean mass transports through both the Den-
 853 mark and Iceland-Scotland straits compared to observations (Shaffrey et al.,
 854 2009). So the tendency to increase the mean AMOC as resolution increases,
 855 demonstrated in our forced model, may be hindered by compensating bi-
 856 ases in coupled models. It is also important to keep in mind the resolution
 857 increase when performing experiments like the ones for this study and for
 858 those conducted by Hodson and Sutton (2012): their highest resolution re-
 859 mains insufficient to resolve mesoscale processes in the subpolar region or in
 860 the subtropical North Atlantic. Hence our results are not directly compara-
 861 ble to theirs, although the methodology may look similar.

863 5.7. *Impact of the nest outside its imprint*

864 The grid refinement over the north Atlantic uses a two-way nesting ap-
 865 proach that allows information exchange from fine to coarse grids. Hence
 866 anomalies arise when comparing ERNA and ORCA_REF outside the nested
 867 area.

868 To the North of the nest, near FRAM strait, an intensified Western Svalbard
 869 Current transports more subtropical water northward, leading to warmer
 870 (0.3°C) and saltier (0.1 PSU) water masses at 500 meter depth. These
 871 changes develop on annual time scale; hence a longer simulation is necessary

872 to assert their overall impact on the Arctic heat budget, and hence ther-
 873 mohaline circulation and other changes rapidly appear immediatly after the
 874 beginning of the simulation. To the west of Svalbard, a strong local warming
 875 (up to 1°C) appears at the surface; its origin remains unclear. At the same
 876 time, a large salinization patch (up to 0.4 PSU) arises along the northeast
 877 Greenland coast over the shelf. The latter seems to be due to an intensified
 878 northward coastal current in ERNA that transports relatively salty water
 879 masses from lower latitudes. Concurrently, we notice 1 Sv cyclonic anomaly
 880 in barotropic stream function around Greenland.

881 To the South of the nest, a large cooling pattern at 500 meter depth devel-
 882 ops (reaching -0.5°C at the end of the simulation) in ERNA compared to
 883 ORCA_REF over a large area of the South Atlantic basin (from the equator
 884 to 35°S). It clearly reflects an oceanic adjustment through rapid (within the
 885 first year) Kelvin waves propagating southward along the American coast, fol-
 886 lowed by Rossby waves propagating westward (on an interannual timescale)
 887 from the African coast, consistent with the theoretical study of Johnson and
 888 Marshall (2002). The process that triggers initial Kelvin waves remains un-
 889 clear, but it is without doubt located within the nest and not present in
 890 ORCA_REF. As for the Arctic, ERNA should be integrated for much longer
 891 time periods in order to clarify the role of these anomalies in the South At-
 892 lantic and beyond.

893 Finally, differences in maximum AMOC between ERNA and ORCA_REF are
 894 visible far beyond the southern boundary of the nest. They increase progres-
 895 sively in time and reach after approximately 15 years, respectively 4.0 Sv, 3.2
 896 Sv and 2.8 Sv at the equator, 20°S and 40°S . We cannot exclude that larger

⁸⁹⁷ AMOC anomalies develop on a longer time scale, as thermohaline properties
⁸⁹⁸ are advected through the South Atlantic to the Southern Ocean.

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899 6. Conclusion

900 In this paper we determine the impact of horizontal resolution on the
 901 North Atlantic western current system and the AMOC, using two hindcast
 902 ocean simulations: ERNA (a $1/8^\circ$ grid refinement over the North Atlantic
 903 embedded in a global ORCA $1/2^\circ$ grid) and ORCA_REF (a global ORCA
 904 $1/2^\circ$ grid only) that have been integrated for 20 years using the same in-
 905 terannual forcing. The higher horizontal resolution clearly leads to large
 906 improvements in the Gulf Stream, North Atlantic Current and Deep West-
 907 ern Boundary Current mean pathways. We perform a detailed analysis of the
 908 DWBC behavior and show that it is stronger in ERNA than in ORCA_REF,
 909 both due to the formation of overly dense water in the Labrador and Irminger
 910 Seas and improved overflows. Besides, we describe substantial changes in the
 911 DWBC pathway between ERNA and ORCA_REF in the intergyre region.
 912 While in ORCA_REF, the DWBC pathway follows a dominant unrealistic
 913 interior route, while it hugs the continental rise in ERNA (with a secondary
 914 interior pathway in agreement with observations, Kieke et al. 2009). Improve-
 915 ments in amplitude and structures of both the upper and deep circulation
 916 all contribute to improving the mean AMOC.

917
 918 When computing the AMOC in density space, which is more adapted
 919 to follow dense water mass transport, the AMOC shape and maximum in-
 920 tensity look very different. The first (second) AMOC maximum arising in
 921 the Subpolar Gyre (at low latitudes near Cape Hatteras) presents a stronger
 922 intensity in ERNA of 6 Sv (up to 8 Sv) than in ORCA_REF. We point out
 923 an important process, setting the AMOC maximum in addition to overflows

924 and convection through the interaction between the upper ocean circulation
 925 and the DWBC mainly near Flemish Cap and Cape Hatteras. This inter-
 926 action seems to control the intensity of the second AMOC maximum at low
 927 latitudes. In ORCA_REF, the decrease of AMOC from the Subpolar to Sub-
 928 tropical latitudes is due to the dominant DWBC interior pathway which does
 929 not allow for a proper interaction with NAC and enhances diapycnal mix-
 930 ing of NADW with surrounding lighter water masses, hence the subsequent
 931 AMOC decrease. Following Hodson and Sutton (2012), density anomalies
 932 linked to deep water formation in high latitudes propagate along the DWBC
 933 down to the subtropics, therefore a biased DWBC interior pathway as simu-
 934 lated in ORCA_REF may potentially affect the AMOC adjustment to high
 935 latitude perturbations, hence its variability. In this framework it would be
 936 interesting to extend this analysis to other low resolution ocean models that
 937 tend to underestimate the AMOC as illustrated in Griffies et al. (2009). The
 938 relative low AMOC intensities [4 - 14 Sv at 45°N] may be partly due to the
 939 DWBC behavior in the intergyre region as illustrated in ORCA_REF.

940
 941 Despite the numerous improvements highlighted in the ERNA experi-
 942 ment, limited salinity and temperature biases remain especially in the subpo-
 943 lar gyre where mesoscale processes are not correctly reproduced and further
 944 resolution increase or specific parameterizations for fine scale processes may
 945 be needed. These biases tend to be amplified as resolution increases, which
 946 may be due to a positive feedback from sea-ice in the Nordic Seas.

947
 948 Due to the two-way nesting, consequences of the increased resolution and

949 associated circulation changes are generated outside the nest boundaries, and
950 these are noticeable. For instance, differences in the AMOC maximum in the
951 North Atlantic propagate into most of the Southern Atlantic and reach al-
952 most 3 Sv at 40°S at the end of the simulation. Thus we anticipate significant
953 changes in the Southern Ocean circulation for longer integrations in ERNA.
954 The same is true for the Arctic Ocean, where substantial changes are already
955 visible, in particular around Greenland. Thus for local and global reasons
956 and because the North Atlantic exerts such an important role in water mass
957 formation, we believe that this configuration could be a good alternative to
958 global high resolution configurations in ocean-only mode as well as coupled
959 to an atmospheric model.

960

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