Journal of Marine Systems 142 (2015) 126–143

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

The North Atlantic subpolar circulation in an eddy-resolving global ocean model

Alice Marzocchi [a,*], Joël J.-M. Hirschi [b], N. Penny Holliday [b], Stuart A. Cunningham [b,1], Adam T. Blaker [b], Andrew C. Coward [b]

[a] School of Ocean and Earth Science, University of Southampton, National Oceanography Centre, European Way, Southampton SO14 3HZ, UK
[b] National Oceanography Centre, European Way, Southampton SO14 3ZH, UK

ARTICLE INFO

Article history:
Received 19 April 2013
Received in revised form 10 October 2014
Accepted 13 October 2014
Available online 30 October 2014

Keywords:
Ocean modelling
Eddy-resolving
NEMO
North Atlantic
Subpolar gyre warming
Physical oceanography

ABSTRACT

The subpolar North Atlantic represents a key region for global climate, but most numerical models still have well-described limitations in correctly simulating the local circulation patterns. Here, we present the analysis of a 30-year run with a global eddy-resolving (1/12°) version of the NEMO ocean model. Compared to the 1° and 1/4° equivalent versions, this simulation more realistically represents the shape of the Subpolar Gyre, the position of the North Atlantic Current, and the Gulf Stream separation. Other key improvements are found in the representation of boundary currents, multi-year variability of temperature and depth of winter mixing in the Labrador Sea, and the transport of overflows at the Greenland–Scotland Ridge. However, the salinity, stratification and mean depth of winter mixing in the Labrador Sea, and the density and depth of overflow water south of the sill, still present challenges to the model. This simulation also provides further insight into the spatio-temporal development of the warming event observed in the Subpolar Gyre in the mid 1990s, which appears to coincide with a phase of increased eddy activity in the southernmost part of the gyre. This may have provided a gateway through which heat would have propagated into the gyre's interior.

1. Introduction

The subpolar North Atlantic is one of the climatically relevant regions of the global ocean (Rhein et al., 2011). This is the first deep-ocean location where water mass transformation actively determines the shape of the Atlantic Meridional Overturning Circulation (AMOC). The subpolar North Atlantic is also a crucial region for the modulation of the temperate climate of north-western Europe, and the dynamics of the Subpolar Gyre (SPG) determine the rate of deep-water formation (Katsman et al., 2004). These newly formed, or significantly modified, water masses constitute the cold lower limb of the AMOC, and variations induced by climate change are most likely to arise in this area.

The SPG is a dominant large-scale feature of the surface circulation of the northwest Atlantic (Higginson et al., 2011) and is characterised by cyclonic rotation. It spans from 45°N to about 65°N (Rhein et al., 2011) and it includes the area of the sills between Greenland, Iceland, the Faroe Islands and Scotland. Waters of tropical and subtropical origin form the warm and salty upper branch of the AMOC; through the Gulf Stream, North Atlantic Current (NAC), and Irminger Current, the AMOC transports these warm and salty waters to the subpolar North Atlantic (Higginson et al., 2011; Käse and Krauss, 1996). Here, the NAC and the Irminger Current release heat to the atmosphere, and the subsequent buoyancy loss leads to the formation of deep and intermediate water throughout the subpolar gyre and notably in the Labrador Sea, from where it is exported as North Atlantic Deep Water (Rhein et al., 2011). The return cold and fresh stream flows along the shelf at the western edge of the basin. This comprises the East Greenland Current and the West Greenland Current, which carry sea-ice and low salinity water from the Arctic and runoff from North America and the Greenland ice cap (Dickson et al., 2007), providing a pathway for the export of fresh water from high latitudes (Higginson et al., 2011). The West Greenland Current flows into the Labrador Current, which exits the Labrador Sea on the western boundary and travels south past Newfoundland. The formation of deep and intermediate waters in the Labrador Sea is one of the major connections between the warm upper branch of the AMOC and its cold lower one, and a crucial process for the intensity of this link is the energy exchange between the atmosphere and the ocean surface (Rhein et al., 2011).

The dense, cold overflows from the Nordic Seas constitute the main source of the southward flow of North Atlantic Deep Water, maintaining the deep branch of the North Atlantic thermohaline circulation (Dickson and Brown, 1994; Eldevik et al., 2009; Hansen and Østerhus, 2000). The greatest volume exchange between the Nordic Seas and the rest of the world ocean occurs across the Greenland–Scotland ridge (Bacon, 2002), which separates these basins from the Atlantic Ocean. This

---

[*] Corresponding author at: School of Geographical Sciences, University of Bristol, University Road, Clifton, Bristol BS8 1SS, UK.
E-mail address: marzocchi.alice@gmail.com (A. Marzocchi).
[1] Now at: Scottish Association for Marine Science, Oban, UK.

http://dx.doi.org/10.1016/j.jmarsys.2014.10.007
0924-7963/© 2014 Published by Elsevier B.V.

ridge system between Greenland, Iceland, Faroe Islands and Scotland acts as a sill, damming up the deep-waters from the Nordic Seas, but allowing the exchange of surface and intermediate waters; some of these exchanges occur as overflows, when dense, cold waters from the Nordic Seas pass over the top of the sill and flow downstream at depth (Bacon, 2002). These processes have a fundamental impact on the circulation in the Labrador and Irminger Seas, which are active sites of deep-water formation. In these regions, wintertime cooling can trigger deep convection down to depths of 1000–2400 m, which results in the formation of an important intermediate water mass, the Labrador Sea Water (LSW). This watermass contributes to the lower limb of the global thermohaline circulation, which is a key process for the transport of heat, freshwater and carbon dioxide in the coupled atmosphere–ocean climate system (Haine et al., 2008; Yashayaev, 2007).

Modelling studies can be particularly useful given that most of the oceanic observational records in the subpolar North Atlantic are quite short and sparse. Estimates of the mean circulation based on such sampling may therefore be seasonally biased, significantly aliasing the low-frequency variability (Higginson et al., 2011). Numerical models represent therefore an invaluable tool to study the dynamics of these regions and to determine the causes of the observed variability, but they first need to be able to realistically simulate the base state of the regional circulation and hydrography (Rhein et al., 2011). Although many studies have shown that high-resolution eddy-permitting models can adequately reproduce the salient features of the circulation in the subpolar region (Tréguier et al., 2005) there are still questions with respect to hydrography and water masses formation (Rattan et al., 2010). For instance, numerical models tend to simulate an unrealistic salinification of the Labrador Sea, which can trigger too-deep convection, and cause an excessive deepening of the mixed layer in this area (Rattan et al., 2010; Treguier et al., 2005). The use of higher resolution, eddy-resolving models (i.e. able to resolve mesoscale eddies) could potentially overcome some of these biases, allowing a more realistic representation of the circulation.

The main limitations of running such high-resolution models are the computational and storage costs. However, state-of-the-art computing facilities allow the performance of relatively long runs with this kind of models, and therefore produce analysis of ocean processes at interannual to multi-decadal timescales. In this study we use a new version of the eddy-resolving ocean general circulation model (OGCM) NEMO (Nucleus for European Modelling of the Ocean) at a resolution of 1/12°, which is being run in its global configuration (ORCA12) by the Marine Systems Modelling group at the National Oceanography Centre, Southampton (NOCS), within the DRAKKAR Consortium (DRAKKAR Group, 2007). We investigate its performance in the North Atlantic subpolar regions, and present a 30-year (1978–2007) global simulation, which represents the longest available for this version of the model with a vertical resolution of 75 levels. The global ocean model configuration and the observational datasets are described in Section 2. In Section 3, we evaluate the representation of the circulation in the subpolar North Atlantic where key processes are analysed in specific areas of interest. Discussion, summary and conclusions are presented in Sections 4 and 5.

2. Methods and data

2.1. Ocean model configuration

The simulation analysed in this study was performed using a refined eddy-resolving OGCM at a resolution of 1/12°, which is part of the NEMO framework of Ocean/Sea-Ice general circulation models (Madec, 2008). NEMO is based on version 9.1 of the OPA primitive equation, free surface ocean general circulation model coupled to the Louvain la Neuve (LIM2) sea ice model (Fichefet and Maqueda, 1997), which is a dynamic–thermodynamic sea ice model with three layers and a viscous-plastic rheology (Renner et al., 2009). This simulation was started using version 3.2 of the model code, which was subsequently updated throughout the run (from model-year 1989 onwards) to version 3.3.1. NEMO uses the quasi-isotropic tripolar ORCA grid (Madec and Imbard, 1996), which becomes finer with increasing latitudes. In the case of ORCA12, the effective horizontal resolution of the common grid ranges between 9.25 km at the Equator, 7 km at Cape Hatteras (mid-latitudes), and 1.8 km in the Ross and Weddell Seas. The standard eddy-resolving ORCA12 configuration has been setup within the DRAKKAR group (e.g. Treguier et al., 2014; Duchez et al., 2014; Deshayes et al., 2013). This ORCA12 global configuration is run with some specific features at NOCS, such as a non-linear free surface to compute the sea surface height (SSH), DFS4.1 surface forcing (Brodeau et al., 2010), and 75 vertical levels. This vertical grid is refined at the surface (1 m for the first level), and has 22 levels in the first 100 m, smoothly increasing to a maximum layer thickness of 250 m at the bottom, with partial steps representing the bottom topography. The bathymetry used in ORCA12 is based on the combination of two databases, GEBCO (IOC, IHO and BODC, 2003) on the continental shelves, and ETOPO2 (U.S. Department of Commerce, 2006) in the open ocean. A free-slip lateral friction condition is applied at the lateral boundaries. A total variance diminishing advection scheme is used for the tracers (Cravatte et al., 2007; Lévy et al., 2001), and the mixing scheme is a turbulent closure model implemented by Blanke and Delecluse (1993).

The run was started from rest in 1978, and initialized from the World Ocean Atlas (WOA) 2005 climatological fields (Antonov et al., 2006; Locarnini et al., 2006). The ocean time step is 200 s and the sea ice model is called at every time step; the simulation is forced by 6-hourly winds, daily heat fluxes, and monthly precipitation fields, with a moderate relaxation of the surface salinity, which is restored to WOA 2005 with a 180-day timescale. The first three years of simulation were run without any constraint on the freshwater budget, but the resulting decrease in global SSH of 20 cm per year was considered unacceptable. This parameterization has therefore been modified, with the freshwater budget being instantly checked and restored when a deficit is found, but the restoring is only applied to areas where there is precipitation. An additional year (2008) has been run at the end of the initial simulation, to allow a more accurate comparison to available hydrographic measurements in the Labrador Sea (as outlined in Section 3.4.3, Fig. 11). This year was run using an updated version of the surface forcing (DFS5.1.1), and it is not included in the general analysis of the model's performance, which only considers the first 30 years of simulation. Model outputs are stored as successive 5-day means throughout the whole integration, and in this study we only consider the North Atlantic region, extracted from the global model output, with a domain spanning from about 90°W to 10°E, and 25°N to 75°N (Fig. 1).

2.2. Volume transport calculation

Full depth volume transport is calculated across five sections covering the main open boundaries of the analysed North Atlantic domain (Fig. 1b). Volume transport time series were produced for the whole duration of the simulation.

The volume transport of the overflows from the Nordic Seas is calculated in temperature classes, both in the Denmark Strait and in the Faroe Bank Channel, where two specific sections have been selected across the two channels, allowing comparison to observations. Temperature classes have been defined as described in Section 3.2, and a mask has been applied to select only the areas characterised by the selected temperature ranges. The volume transport is calculated as the velocity field (its meridional component in the Denmark Strait, and its zonal component in the Faroe Bank Channel) multiplied by