Ocean Modelling 45–46 (2012) 59–80

Contents lists available at SciVerse ScienceDirect

Ocean Modelling

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

Mechanisms of subantarctic mode water upwelling in a hybrid-coordinate global GCM

Hao Zuo[a,d,*], Alberto C. Naveira Garabato[a], Adrian L. New[b], Andreas Oschlies[c]

[a] School of Ocean and Earth Science, University of Southampton, National Oceanography Centre, Southampton SO14 3ZH, UK
[b] National Oceanography Centre, Southampton SO14 3ZH, UK
[c] Leibniz Institute of Marine Science (IFM-GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany
[d] Environmental Systems Science Centre (ESSC), University of Reading, Reading RG6 6AL, UK

ARTICLE INFO

Article history:
Received 22 July 2011
Received in revised form 26 November 2011
Accepted 19 December 2011
Available online 8 January 2012

Keywords:
SAMW
HYCOM
Tracer upwelling
Numerical mixing
Nutrient circulation
Induction

ABSTRACT

This article presents an investigation of the global circulation and upwelling of subantarctic mode water (SAMW), which is thought to be key in the supply of nutrients to support biological production over much of the world ocean excluding the North Pacific. The HYbrid isopycnic-cartesian Coordinate Ocean general circulation Model (HYCOM) is configured to simulate the global ocean circulation for time scales of up to centuries and a SAMW-tracking online tracer experiment is conducted. The tracer re-emergence fluxes across the mixed layer base effected by a range of physical mechanisms and by numerical mixing terms in HYCOM are diagnosed and discussed. For the global ocean north of 30°S, entrainment due to surface buoyancy loss and/or wind-induced mechanical stirring accounts for almost one third of the total tracer re-emergence. Ekman upwelling and shear-induced mixing are especially significant in the tropical oceans, and account for 19% and 18% of the total tracer re-emergence, respectively. There is substantial regional variation in the relative importance of the various upwelling mechanisms. Special attention is devoted to understanding the contrasting circulations of SAMW in the North Pacific and North Atlantic oceans. The modest penetration of SAMW into the North Pacific is found to arise from the comparatively light density level that the SAMW core resides at in the South Pacific Ocean, which results in its being captured by the Equatorial Undercurrent and prevents it from entering the western boundary current of the North Pacific. In the North Atlantic, a new conceptual model of SAMW circulation and re-emergence is proposed with application to nutrient supply to the regional upper ocean. The model formulates SAMW re-emergence as a sequence of distinct processes following the seasonal cycle of the thermocline as a water column circulates around the subtropical and subpolar gyres of the North Atlantic.

1. Introduction

Marine biological production and its role in the global carbon cycle are controlled by the supply of inorganic nutrients (in particular, nitrate, phosphate and silicate), which are constantly removed from the euphotic surface waters by growing phytoplankton (Hecky and Kilham, 1988; Sarmiento et al., 2004). Both global-scale and small-to-mesoscale processes can be significant in returning nutrients from the ocean interior to the euphotic zone. The overturning circulation plays a dominant role in distributing nutrients from their source region (most notably the Southern Ocean, where large amounts of nutrients are subducted without being utilized by primary producers) to the global ocean on multi-annual to centennial time scales. On smaller length scales and seasonal timescales, convection (entrainment) and upwelling driven by surface buoyancy fluxes and mechanical wind forcing (Marshall and Schott, 1999; Williams and Follows, 1998) are important in transporting nutrients vertically from the thermocline into the overlying euphotic zone. Ekman divergence is normally considered significant in sustaining a band of upwelling along the equator (Wyrtki, 1981; Johnson et al., 2001) and in the eastern boundary regions (Smith, 1995; Hutchings et al., 1995). Eddies can help to supply nutrients via eddy pumping effects (McGillicuddy and Robinson, 1997; McGillicuddy et al., 1998; Naveira-Garabato et al., 2004) or via lateral stirring (Oschlies, 2002). Diapycal diffusion can also be important, especially in regions with strong turbulent activity (Jenkins and Doney, 2003). Even though the physical mechanisms that affect the nutrient transport in the ocean interior have been investigated extensively, the global picture of the relative importance of the nutrient supply mechanisms to the upper ocean is relatively poorly understood.

Through combining the observed distributions of both silicate and nitrate, Sarmiento et al. (2004) tracked the main nutrient

---

* Corresponding author at: Environmental Systems Science Centre (ESSC), University of Reading, Reading RG6 6AL, UK. Tel.: +44 (0) 118 378 5204; fax: +44 (0) 118 378 6413.
E-mail address: hzu@mail.nerc-essc.ac.uk (H. Zuo).

1463-5003/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ocemod.2011.12.006

subduction pathway from deep waters upwelled in the Southern Ocean. The Southern Ocean has long been recognized as playing a central role in the global carbon cycle and biological productivity (Sarmiento et al., 1998; Sigman and Boyle, 2000). Their results show that it is the SAMW, which forms in the nutrient-rich Subantarctic Zone and subsequently subducts and spreads through-out the entire Southern Hemisphere and North Atlantic Ocean, that mediates the supply of nutrients upwelled in the Southern Ocean to the global pycnocline and, ultimately, upper ocean mixed layer. This role of SAMW as the main conduit of nutrients from the Southern Ocean to the upwelling regions of the equatorial Pacific and off South America was studied by Toggweiler et al. (1991). Williams et al. (2006) used an isopycnal OGCM configured for the Atlantic Ocean to investigate the source for the nutrient supply to the North Atlantic Ocean and suggested that the relatively high nutrient concentration of the Gulf Stream may also have its source in the SAMW. As a result, determining the formation of this specific mode water in the Southern Ocean, its subsurface circulation pathways in the world ocean and its eventual re-emergence in the three major ocean basins is a significant step in understanding how biological production in the global ocean euphotic zone is sustained.

Using a high-resolution numerical model, Ribbe and Tomczak (1997) examined the ventilation pathway of SAMW in the Southern Ocean (south of 12°S) through off-line tracer experiments. Sloyan and Kamenkovich (2007) evaluated the simulation of SAMW and Antarctic Intermediate Water (AAIW) in eight IPCC climate models relative to the Commonwealth Scientific and Industrial Research Organization Atlas of Regional Seas 2006, but also confined their study to the Southern Hemisphere. A further study of Southern Hemisphere ventilation was recently carried out by Sen Gupta and England (2007), in which a set of tracer release experiments were conducted in a globally configured eddy-permitting model. An important source of error in those ocean models is the often inadequate representation of subgrid-scale mixing processes and the poor control of numerical mixing effects. As a consequence, the re-emergence of SAMW into the upper ocean mixed layer is the most poorly understood and least discussed stage in the water mass' circulation, despite being central to the biogeochemical significance of SAMW.

The mechanisms of SAMW upwelling across the base of the upper-ocean mixed layer is a process that is difficult to represent to an adequate standard in z-level models (Griffies et al., 2000; Lee et al., 2002). Therefore, the HYbrid Coordinate Ocean circulation Model (HYCOM) (Bleck, 2002; see also Chassignet et al., 2003; Halliwell, 2004; Shaji et al., 2005; Kara et al., 2008) is used in this study. A secondary goal of the present study is to assess the limitations of a state-of-the-art hybrid-coordinate model in representing exchanges between the upper-ocean mixed layer and the ocean interior. This paper is arranged as follows. In Section 2, we offer a brief description of the HYCOM model and the configuration used in this study. In Section 3, the design of a tracer experiment for simulating the formation, circulation and upwelling of SAMW is characterised. Section 4 discusses a scheme for decomposing re-emergence across the base of the upper-ocean mixed layer in terms of contributions from different physical processes and numerical effects in HYCOM. Results on the re-emergence of SAMW in the global ocean analyzed according to our decomposition scheme are given in Section 5. Finally, Section 6 summarizes the conclusions of this work.

2. Configuration of numerical model

The numerical model used for this study is HYCOM (Peters et al., 1988; Bleck, 2002; Chassignet et al., 2003) with a K-Profile Parameterization (KPP) mixing scheme (Peters et al., 1988; Large et al., 1994, 1997). HYCOM is formulated in isopycnal coordinate in the interior stratified ocean, and in *z*-coordinate in the weakly-stratified mixed layer, with a transition zone in between. The vertical re-positioning of the coordinate interfaces, triggered by the potential density deviation from the target density of the isopycnal layers in each model time step, is central to the model procedure and is referred to as the re-gridding process (Bleck, 2002; Chassignet et al., 2003). The model is in a near-global configuration, covering a horizontal domain from 78°S to 69°N, and 0°E to 360°E, with a uniform projection and at $3 \times 3°$resolution. The model domain includes the entire Southern Ocean and most of the high-latitude area of the North Atlantic (including the Greenland – Iceland – Scotland Ridge, but excluding the Arctic Ocean). Two closed walls are placed at the northern and southern boundaries and there are no fluxes crossing them. The bathymetry for the model was derived from the 5-min ETOPO5 database with no additional smoothing applied. The minimum depth of the ocean was set to 10 m. There are 16 isopycnal layers (Table 1) of constant potential density (except for the near-surface *z*-coordinate regions), varying from 30.90 to 37.23 (σ_2, with reference pressure of 2000 dbar to give the best representation of the global circulation). The target densities for isopycnal layers are chosen to represent the water masses and thermocline structure as closely and evenly as possible (Fig. 1). The model is initialized from a state of rest using the Levitus (1982) monthly climatological dataset for temperature and salinity, which is also used for surface relaxation and for applying lateral boundary nudging as described further below.

A surface salinity relaxation is applied to the control simulation, in order to prevent precipitation–evaporation induced model drift away from observed salinity, with a time scale of 5 months for a 100 m mixed layer thickness. Boundary relaxations are also applied near the Strait of Gibraltar (with a time scale of 20 days), the Greenland–Iceland–Scotland ridge (10–100 days, relaxation strongest at the boundary) and the model domain's southern boundary (250–1000 days), in order to account for the influence of the Mediterranean Water inflow, deep water formation north of the model domain, and production of Antarctic Bottom Water (AABW), respectively. The control run is undertaken for 120 years and forced by NCEP/NCAR monthly wind stress, heat flux, precipitation and evaporation fields (Kalnay et al., 1996), until the model reaches a quasi-equilibrium state (Fig. 2). The meridional overturning stream functions for the Atlantic, Pacific, and Indian oceans are computed from the control run and illustrated in Fig. 3. Two cells of the global meridional overturning circulation (MOC) can be identified, with an amplitude of about 37.5 Sv for the abyssal cell associated with the northward export of AABW; and 17.5 Sv for the mid-depth cell associated with the southward flow of upper

Table 1
Target potential densities for HYCOM layers with reference to pressure of 2000 dbar.

Layer number	Potential density (σ_2)
1	30.90
2	31.87
3	32.75
4	33.54
5	34.24
6	34.85
7	35.37
8	35.80
9	36.15
10	36.43
11	36.65
12	36.81
13	36.96
14	37.07
15	37.16
16	37.23