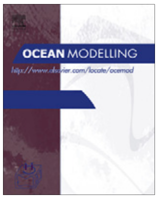
Ocean Modelling 36 (2011) 133–148

Contents lists available at ScienceDirect

Ocean Modelling

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



How does the Red Sea outflow water interact with Gulf of Aden Eddies?

Mehmet Ilıcak[a,*], Tamay M. Özgökmen[b], William E. Johns[b]

[a] Princeton University, AOS, NJ, USA
[b] RSMAS, 4600 Rickenbacker Causeway, Miami, FL 33149, USA

ARTICLE INFO

Article history:
Received 13 August 2010
Received in revised form 22 September 2010
Accepted 28 October 2010
Available online 10 November 2010

Keywords:
Red Sea overflow
Gulf of Aden eddies
Gravity current
Mixing

ABSTRACT

As the Red Sea overflow water (RSOW) enters the Gulf of Aden (GOA), it interacts with a sequence of nearly barotropic, mesoscale eddies originating in the Indian Ocean. To investigate how these eddies impact the dispersal and eastward transport of the RSOW toward the Indian Ocean, a high resolution 3D regional model is employed to explore systematically the interaction between the RSOW and mesoscale eddies. Two types of experiments are conducted. In the first set, we simulate the behavior of RSOW in the presence of an idealized cyclone and an idealized anticyclone. The second type of simulation involves nesting of the regional model (ROMS) within a data-assimilating global model (HYCOM), in which a sequence of mesoscale eddies entering the Gulf of Aden is realistically captured. This simulation is integrated for one year, and includes a simple representation of the seasonality of the RSOW.

Bower et al. (2002) suggest that the Red Sea overflow might be a western boundary undercurrent. Consistent with these expectations, the idealized simulations show that the preferred pathway of the RSOW in the absence of eddies is along the coast of Somalia (southern continental shelf) as a western boundary undercurrent. Simultaneously, a cyclonic circulation is generated in the far western GOA due to vortex stretching by the descending outflow. The presence of a cyclone in the western GOA increases the peak RSOW transport, but the cyclone itself rapidly loses its coherence after interacting with the rough topography in the western GOA. The presence of an anticyclone tends to block the preferred boundary pathway and inhibits the eastward transport of the RSOW. The eddies also result in substantially increased mixing of the RSOW in the western GOA.

On the basis of the more realistic ROMS experiment, it is found that the modeled RSOW leaves the western part of the Gulf of Aden in short episodic bursts with transports that are an order of magnitude greater than that associated with the quasi-steady RSOW inflow into GOA. Such enhancement in RSOW transport is shown to be induced by cyclonic eddies that cause a rapid discharge of RSOW from the western part of the GOA. We conclude that mesoscale eddies play a key role in the transport and mixing of the RSOW within GOA.

1. Introduction

Saline, dense Red Sea deep water is formed in the northern Red Sea due to excessive evaporation and exits the Red Sea as a dense overflow through the Bab al Mandeb strait (Murray and Johns, 1997; Morcos, 1970). As it enters the western Gulf of Aden (GOA), it divides into two channels: a very narrow (~5 km wide), long northern channel and a broader, shorter southern channel (Bower et al., 2005; Peters et al., 2005). It then reaches neutral buoyancy at different depths in the western GOA and spreads laterally through the Gulf. According to observations, the Red Sea outflow becomes a major intermediate water mass in the Indian Ocean (Beal et al., 2000). The properties of this water mass are modified by the mixing and stirring processes that take place in the GOA (Bower et al., 2005). Although the annual mean volume transport of the Red Sea overflow water (≈0.37 Sv where $1\ \mathrm{Sv} \equiv 10^6\ \mathrm{m^3/s}$) is relatively small compared to major overflows such as the Mediterranean overflow (≈1 Sv) or the Denmark Strait overflow (≈2.9 Sv) (Murray and Johns, 1997; Candela, 2001; Girton et al., 2001; Macrander et al., 2007), it has a distinctive and far reaching signal. The Red Sea overflow water has been observed as far as the Agulhas Current (Roman and Lutjeharms, 2007), from which it seems to be transported to the South Atlantic.

Modeling of the Red Sea overflow is a challenging problem because of demands on resolution to be fine enough to resolve the channels and accuracy of mixing parameterizations. There are only few studies in which it was attempted to model the Red Sea outflow. Özgökmen et al., 2003 and Ilıcak et al., 2008b used 2D non-hydrostatic models to reproduce the Red Sea gravity current in the northern channel. Chang et al., 2008 and Ilıcak et al., 2008a

---

* Corresponding author. Address: Mehmet Ilıcak. 201 Forrestal Road Princeton, NJ 08540, USA. Tel.: +1 7863251094.
E-mail addresses: milicak@princeton.edu, milicak@rsmas.miami.edu (M. Ilıcak).

1463-5003/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ocemod.2010.10.006

modeled the Red Sea overflow using different mixing parameterizations in 3D hydrostatic models and conducted a detailed comparison with data from the 2001 Red Sea Overflow Experiment (REDSOX). In Fig. 1, the bottom layer salinity field is shown from one of our simulations. It can be seen that the northern channel carries most of the overflow, consistent with observations that show that the northern channel transports about two-thirds of the total Red Sea overflow (Matt and Johns, 2007). The total Red Sea Overflow Water (RSOW) transport is around 0.56 Sv at the exit of the channels, where the dense plumes separate from the bottom at the edge of the Tadjura Rift (Fig. 1). The two branches of the overflow equilibrate at different depths in the western GOA; around 800 m for the northern channel flow, and around 550 m for the southern channel flow. Peters et al., 2005 defined two distinct layers to describe the vertical structure of the descending overflow in the channels, a bottom layer (BL), and an overlying interfacial layer (IL). The former reaches from the bottom to a height where the velocity is maximum, and the latter extends from this maximum upward with strong stratification and large shear. The BL is well-mixed and maintains high salinities along the northern channel. In contrast, the IL shows stronger entrainment and carries most of the overall plume transport, increasingly so with downstream distance. However, previous numerical studies have focused on accurate modeling of the Red Sea overflow in a limited basin and excluded any consideration of what happens to the RSOW beyond the Tadjura Rift.

The surface circulation in the GOA is dominated by seasonal wind forcing and a series of mesoscale eddies (Fratantoni et al., 2006; Al Saafani et al., 2007). The size of these eddies can be as large as the width of the Gulf ($\sim$200 $-$300 km) and their azimuthal speed can be as high as 0.5 m/s (Fig. 2). Bower et al., 2002 find that the cyclonic and anticyclonic eddies are in fact nearly barotropic and can reach as deep as 1500 m.

There are different theories for the generation of GOA eddies. Fratantoni et al. (2006) described the passage of a series eddies into the Gulf mostly during the transition between summer and winter monsoons. They showed that the dominant mechanism for these eddies are the instabilities and retroflection of the Somali Current due to monsoon winds. Al Saafani et al. (2007) showed that some of the eddies also propagate into the GOA from the Arabian Sea. The dynamics of these eddies involve interactions with westward propagating Rossby waves generated in the Indian Ocean by poleward propagating Kelvin waves during the winter monsoon (Al Saafani et al., 2007).

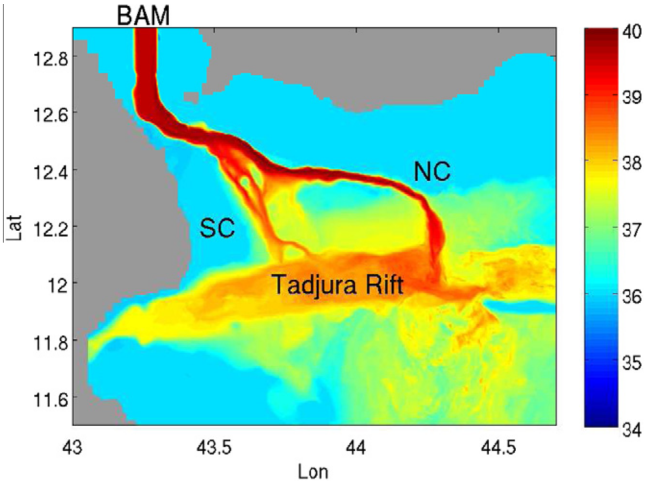


Fig. 1. Maximum salinity [psu] values in the whole water column at time = 120 - days. The overflow has separated into the northern and the southern channels. BAM = Bab al Mandeb, NC = Northern Channel, SC = Southern Channel. The overflow splits into two at Lat $\approx$12.4°N and both plumes separate from the bottom at the Tadjura Rift.

Even though these eddies are now relatively well documented, their effect on the RSOW remains unknown. Aiki et al., 2006 employed a 3D global ocean circulation model to understand characteristics of the Red Sea outflow in the GOA. Their model resolution was not high enough to capture the channels, hence all of the outflow followed the northern channel only. Since the southern channel is not included in that model, they did not simulate the multilayer structure of the Red Sea overflow in the GOA. Aiki et al., 2006 found that the discharged Red Sea outflow and incoming Indian Ocean intermediate water are characterized by anticyclonic and cyclonic circulation, respectively.

In this paper, we study the interaction between the RSOW and GOA eddies. Our objective is to address the following questions:

(a) How is the RSOW transported through the mesoscale eddy field in the Gulf of Aden?
(b) Is there a preferred pathway of the Red Sea overflow out of Gulf of Aden?
(c) Do the eddies act to homogenize the RSOW? If not, how do they influence the fate of this overflow?

Since the interaction between the overflow and multiple eddies can be complex, we start with a simplified problem, and then progress to a more realistic setting. We first consider the overflow in the absence of any eddies in the GOA. After that, an idealized cyclone or anticyclone is initialized with the overflow in two cases. Our focus is on the pathway of the overflow in the presence of an idealized eddy. We then move to a more realistic simulation using a global ocean circulation model including multiple, propagating eddies in the GOA. The overflow transport and mixing in different simulations are also computed for quantitative analysis. To our knowledge, this is the first time that a set of detailed and systematic numerical simulations have been conducted to understand the interaction between the Red Sea overflow and GOA eddies.

Our main finding is that GOA eddies can modulate the transport of RSOW significantly such that RSOW leaves the western half of the GOA in short episodic burst with transports reaching 6 Sv, which is an order of magnitude larger than the steady transport of RSOW out of the channels. Such enhancement of the RSOW transport within the GOA is shown to be induced by cyclonic GOA eddies, while anticyclonic eddies tends the block the eastward propagation of the RSOW. GOA eddies have speeds comparable to RSOW during its descent from the Bab al Mandeb (BAM) Strait. Cyclonic eddies propel RSOW eastward by acting over a much larger cross-sectional area when compared to that of the BAM, resulting in a rapid discharge of RSOW from the western part of the GOA.

This paper is organized as follows: The numerical model and setup of the numerical experiments are introduced in Section 2. The main results are presented in Sections 3 and 4 for idealized and realistic simulations, respectively. We provide a discussion on the time-varying export of RSOW from the western Gulf of Aden and the enhanced growth of the RSOW transport caused by the eddies in Section 5. Finally, we summarize and conclude in Section 6.

2. Model setup

In this study, Regional Ocean Modeling System (ROMS) is chosen as the numerical model. ROMS is a free-surface, hydrostatic, primitive equations ocean model that uses orthogonal curvilinear horizontal coordinates on an Arakawa C grid. The primitive equations are discretized over topography in the vertical using stretched terrain-following, or "sigma", coordinates (Shchepetkin and McWilliams, 2005). The model domain covers the area