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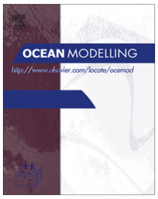

Development of a regional model for the North Indian Ocean

Hasibur Rahaman[a,*], M. Ravichandran[a], Debasis Sengupta[b], Matthew J. Harrison[c], Stephen M. Griffies[c]

[a] *Indian National Centre for Ocean Information Services, Ministry of Earth Sciences, Hyderabad, India*
[b] *Center for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, India*
[c] *National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory (GFDL), Princeton University Forrestal Campus, Princeton, USA*

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ABSTRACT

We have developed a one-way nested Indian Ocean regional model. The model combines the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory's (GFDL) Modular Ocean Model (MOM4p1) at global climate model resolution (nominally one degree), and a regional Indian Ocean MOM4p1 configuration with 25 km horizontal resolution and 1 m vertical resolution near the surface. Inter-annual global simulations with Coordinated Ocean-Ice Reference Experiments (CORE-II) surface forcing over years 1992–2005 provide surface boundary conditions. We show that relative to the global simulation, (i) biases in upper ocean temperature, salinity and mixed layer depth are reduced, (ii) sea surface height and upper ocean circulation are closer to observations, and (iii) improvements in model simulation can be attributed to refined resolution, more realistic topography and inclusion of seasonal river runoff. Notably, the surface salinity bias is reduced to less than 0.1 psu over the Bay of Bengal using relatively weak restoring to observations, and the model simulates the strong, shallow halocline often observed in the North Bay of Bengal. There is marked improvement in subsurface salinity and temperature, as well as mixed layer depth in the Bay of Bengal. Major seasonal signatures in observed sea surface height anomaly in the tropical Indian Ocean, including the coastal waveguide around the Indian peninsula, are simulated with great fidelity. The use of realistic topography and seasonal river runoff brings the three dimensional structure of the East India Coastal Current and West India Coastal Current much closer to observations. As a result, the incursion of low salinity Bay of Bengal water into the southeastern Arabian Sea is more realistic.

1. Introduction

Interaction between the Indian Ocean and the tropical atmosphere plays an important role in climate variability on both regional and global scales (e.g., Vecchi and Harrison, 2002; Annamalai and Murtugudde, 2004; Schott et al., 2009). The tropical Indian Ocean and the land around its rim experience the most energetic component of the climate system, the Asian–Australian–African Monsoon. In recent years, the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) was established to help understand the role of Indian Ocean in monsoon variability (McPhaden et al., 2009) on intraseasonal to interannual time scales.

The main thermocline is deeper than the mixed layer base over most of the Indian Ocean basin. This feature results in a near surface density structure unconstrained by large-scale ocean dynamics, at least on relatively short time scales. Therefore, the near-surface ocean is readily modulated by winds and buoyancy fluxes associated with intra-seasonal variability of the monsoon (Goswami et al., 2012), particularly over the North Indian Ocean. Beyond its potential role in monsoon variability, studies of the Indian Ocean Dipole or Zonal Mode (Saji et al., 1999; Webster et al., 1999; Saji et al., 2006) suggest an important climatic role of Indian Ocean SST both within the region and in other sectors of the globe. Schott et al. (2009) point out a number of deficiencies in ocean model simulations of the Indian Ocean on seasonal, intra-seasonal, and inter-annual time scales, largely attributed to the representation of ocean physical processes. His results provide a mandate for the present study, in which we pay particular attention to the model configuration requirements for better representation of the upper layers of the North Indian Ocean.

The Bay of Bengal (BoB) receives excess fresh water (FW) from precipitation and river runoff that enables relatively strong haline stratification in the top 10–20 m (Sengupta et al., 2006). A paucity of ocean in situ data, and the spatial smoothing used to create gridded climatologies, result in only a weak version of the upper ocean haline stratification in such global products (e.g., Conkright et al., 1998) relative to that found in focused observation-based analyses

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* Corresponding author. Address: Indian National Centre for Ocean Information Services, Ministry of Earth Sciences, Government of India, Ocean Valley, Pragathi Nagar (BO), Nizampet (SO), Hyderabad 500090, India. Tel.: +91 40 23886052/6000; fax: +91 40 23882910.

E-mail address: rahman@incois.gov.in (H. Rahaman).

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(Sengupta et al., 2006; Shetye et al., 1993). Recent models have included realistic FW forcing, yet they have difficulty reproducing the observed features of the salinity distribution, especially in BoB and southeastern Arabian Sea (de Boyer Montégutet et al., 2007; Durand et al., 2007; Han et al., 2001; Han and McCreary, 2001; Kurian and Vinayachandran, 2006). Deficiencies in the parameterization of air–sea fluxes, ocean dynamics and mixing are potential contributors to the lack of model fidelity. A particularly tough challenge for an Indian Ocean model is to simulate this shallow haline stratification, and we focus on the realism of this feature in the regional simulations documented here.

In the North Indian Ocean (NIO), particularly over BoB and the southeastern Arabian Sea the presence of freshwater on top of salty dense water leads to strong stratification within the surface layer. The warm "barrier" layer between the base of the mixed layer and the top of the seasonal or main thermocline (Godfrey and Lindstrom, 1989; Thadathil et al., 2007) inhibits entrainment cooling of the mixed layer. The impact of surface heat fluxes is confined to the shallow mixed layer, rapidly warming or cooling the ocean surface. A barrier layer often exists over the southeastern Arabian Sea (Shenoi et al., 2004), in the Bay of Bengal (Vinayachandran et al., 2002; Thadathil et al., 2007), and south of Indonesia (Qu and Meyers, 2005). A proper representation of the barrier layer requires relatively fine upper ocean vertical grid spacing, such as the 1 m chosen for our simulations.

In addition to impacts from river runoff, Indian Ocean salinity distribution is also affected by the influx of relatively fresh Pacific water in the Indonesian Throughflow (ITF), and salty water from the Persian Gulf and Red Sea. In many regional Indian Ocean studies, the models are configured with closed (sponge) boundaries in the east and south of the domain (Kurian and Vinayachandran, 2006; Perigaud et al., 2003; Han et al., 2001). Closing these boundaries can result in unrealistic salinity distributions due to the absence of ITF impacts (Bray et al., 1997). For example, Zhang and Marotzke (1999) show an increase of SSS by 0.2–0.4 psu over entire Indian Ocean when the ITF is closed. We therefore pay particular attention in our study to the needs of prescribing realistic lateral boundary properties to help ensure a realistic salinity distribution within the Indian Ocean.

Mesoscale eddies, narrow boundary currents, and flows through narrow passages are important elements of the Indian Ocean circulation. Along with the importance of the upper ocean haline stratification, these features require sufficiently fine horizontal and vertical resolution to properly represent. Coupling a global OGCM to a finer resolution regional model provides one means to make progress using limited computational resources while facilitating a wide suite of physical and biogeochemical processes. The use of such regional models has increased in recent years, in particular due to the development of operational oceanography. We take this approach in the present study.

One-way nested regional models have been developed with great success for instance in the California Current region (Penven et al., 2006). The approach adopted in the present study to handling the open boundaries (OBCs) is less sophisticated but considered sufficient for the present work. Details of the model configuration (e.g., bathymetry, geography, forcing) determine the OBC method most suitable for a particular configuration (e.g., Herzfeld et al., 2011).

We focus in this paper on the implementation of an open boundary formulation for a regional Indian Ocean model that is one-way nested into a coarser resolution global model. Notably, the global model and regional model use the same code (MOM4p1; Griffies, 2009) along with the same surface boundary forcing and matching topography at the open boundaries. We focus on the upper ocean temperature and salinity structure in the simulation, with special emphasis on the Bay of Bengal given its importance for Indian Ocean circulation and variability. In Section 2, we describe the data used, model configuration, and the experiments performed. In Section 3 we present an analysis of the simulations and provide discussion. We offer summary and conclusions in Section 4.

2. Model configurations, data and experiments

2.1. Model description

We make use of the Modular Ocean Model (MOM4p1; Griffies, 2009) for both the regional and global configurations used in this study. The global configuration follows that used for the earth system model documented by Dunne et al. (2012), which is an updated version of the configuration documented by Griffies et al. (2005), Delworth et al. (2006) and Gnanadesikan et al. (2006). We summarize here some of the key features of this configuration and note where it differs from the regional configuration.

The vertical grid used in the global model has 50 vertical z^* coordinate levels, with 10 m grid spacing in the upper 220. The horizontal grid spacing is 1° with the meridional spacing refined to 1/3° within the equatorial waveguide. The model uses the KPP vertical mixing scheme to parameterize upper ocean boundary layer processes (Large et al., 1994). Rotated neutral diffusion of tracers (Griffies et al., 1998) and an eddy-induced advective transport (Gent and McWilliams, 1990; Griffies, 1998) are used to parameterize mesoscale eddy transport. A biharmonic lateral viscosity parameterization (Griffies and Hallberg, 2000) with western boundary enhancement is used in addition to a harmonic frictional operator. We include the Fox-Kemper et al. (2011) parameterization of sub-mesoscale mixed layer re-stratification. Shortwave penetration depth varies spatially and climatologically based on a global chlorophyll dataset (Manizza et al., 2005; Anderson et al., 2007). Topography is represented by the partial step formulation of Pacanowski and Gnanadesikan (1998). Tidal amplitudes in parts of the North Indian Ocean (NIO) can be large, and the shelf can be wide, as in the northern Bay of Bengal. An internal tidal mixing scheme (Simmons et al., 2004) parameterizes diapycnal mixing over rough topography where stratification exists at depth. Additionally, the frictional dissipation of barotropic tidal energy and subsequent diapycnal tracer mixing is parameterized separately as in Lee et al. (2006).

The regional model configuration refines the grid from the nominal 1° in the global model to $0.25° \times 0.25°$ horizontal resolution. The vertical grid is also refined in the upper ocean (Fig. 1). We chose the regional model domain by considering dynamical as well as thermodynamical aspects of the North Indian Ocean as motivated by the study of Schott et al. (2009). In particular, the southern boundary at 30°S is chosen to include the Indian Ocean subduction zone (see Fig. 6 from Schott et al., 2009). Additionally, the earlier regional model study of Kurian and Vinayachandran (2006) uses the same domain used in the present study. The vertical physical parameterizations used in the regional model are identical to the global simulations (Table 1). In contrast, the mesoscale eddy parameterizations (neutral diffusion and eddy-induced advection) are disabled since the first baroclinic Rossby deformation radius is reasonably resolved for the model domain, although we do not presume 25 km fully resolves all mesoscale features. Horizontal harmonic and bi-harmonic eddy viscosities are retained but with reduced coefficients compared to the global simulation.

The western and northern boundaries of the Indian Ocean region are bounded by land. For the eastern and southern boundaries, an active boundary condition is used for the regional model that requires the mass transport and elevation on the boundary to be known a priori (Flather, 1976). Monthly depth-