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Surface circulation and temperature inversions in the western Bay of Bengal using MITgcm

KEYWORDS: Bay of Bengal, MITgcm, Circulation, Temperature inversion.

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ABSTRACT *The sea surface circulation and the vertical temperature structure along the east coast of India is studied using a 3D numerical model, Massachusetts Institute of Technology general circulation model. This model is configured for the western continental shelf of the Bay of Bengal with bathymetry derived from Earth TOPOgraphy datasets; temperature and salinity from World Ocean Atlas 2009; wind from satellite datasets. The simulations for pre-monsoon, summer monsoon and winter monsoon are studied in detail. The northward flowing western boundary current and southward flowing east India coastal current is captured very well by the model simulations and compared with the observed OSCAR currents. The simulated temperature inversions during the winter months is compared with observed ARGO datasets off Paradeep and Visakhapatnam and is found to be nearly 2°C.*

Introduction:

The Bay of Bengal (BoB) forms the north-eastern part of the Indian Ocean. The peculiarity of this region is its reversing monsoonal winds and its low salinity surface water caused by large river runoff from the distributaries of the major rivers that flow into the Bay. This monsoon arises because of the great pressure changes, which occur between the summer and winter months over the land masses of Asia. Broadly the seasons are divided in context of monsoon (Varkey et al. 1996) that are as follows: (a) Pre-summer monsoon (April-May) (b) Summer monsoon/South-west monsoon (June-September) (c) Post-summer monsoon (October-mid November) (d) Winter monsoon or North-east monsoon (mid November-March).

For BoB, the circulation is mainly influenced by seasonal wind and fresh water discharge into the Bay from the major river systems. The seasonal wind system induces corresponding seasonal currents in the Bay due to their direct or indirect influences. During the south-west monsoon the wind system is almost south-westerly in May signifying the onset of the monsoon in the Bay. By June south-westerly winds prevail almost all over the Bay with high wind speed throughout the months of July and August while during September its intensity decreases signifying the withdrawal of monsoon. These winds produce an easterly drift in the open waters of the Bay, setting a current northward and north-eastward along the east coast of India. The precipitation during this period exceeds evaporation attaining a peak in September/October and resulting fresh water discharge that is high in the northern part. The north-east monsoon starts by November in which north-east trade winds set in through the eastern half of the Bay showing the presence of easterly winds. During December and January, the total bay feels the north-easterly winds while in February its intensity decreases. These winds produces a westerly drift in the open waters of the Bay and flows along the east coast of India south-westerly to southerly current (Reddy, 2001). Temperature inversions (TI) occur during this monsoon period and is defined as a phenomena when the surface water cools trapping the hot water at the sub-surface. In the northern and the western Bay of Bengal surface layer rapidly cools in winter and slowly fades away with the end of winter monsoon. In short "fresh water flux leads the occurrence process in association with surface heat flux and advection" (Tadathil et al. 2002).

With the advent of the 3D numerical models, large scale to small scale oceanic processes studies are in progress in the Indian Ocean in the recent years. Paul et al. (2009) using multi-layered modular ocean model and showed the semi-annual variability of the upper layer circulation along with seasonal variations of circulation, temperature, and salinity. Sil et al. (2010) simulated the circulation features both western boundary current (WBC) and east India coastal current (EICC) utilizing Regional Ocean Modelling System (ROMS) and compared the result with ARGO datasets. Babu and Rao, (2011) simulated the temperature inversions in the BoB using Princeton Ocean Model (POM) and analysed their effect on the internal waves. Massachusetts Institute of Technology general circulation model (MITgcm) has been employed for the first time in the western Bay of Bengal to study the circulation features, temperature inversions for all the seasons and the results are compared with the available ARGO and OSCAR data.

Model configuration and simulation design:

Numerical models have become an indispensable tool in the recent years to investigate various processes in oceans. MITgcm (Marshall et al. 1997a) is a 3D primitive equation model designed for both oceanic and atmospheric phenomena and is available to the community (http://mitgcm.org/). It's a z-coordinate finite volume model that solves the incompressible Navier-Stroke equations with Boussineq approximation on an Arakawa-C grid. The model uses polynomial equation of state (McDougall et al. 2003) and its topography is represented by lopped cells (Adcroft et al. 1997) which is essential for accurate representation of the bottom bathymetry. The model is configured along the east coast of India extending from 12°N to 21.5°N in latitude and from 78°E to 90°E in longitude bearing 280x220x23 grid points in x, y and z axis respectively shown in fig. 1. The domain consists of stations like Chennai, Visakhapatnam, Gopalpur, Chilika and Paradeep along the east coast.

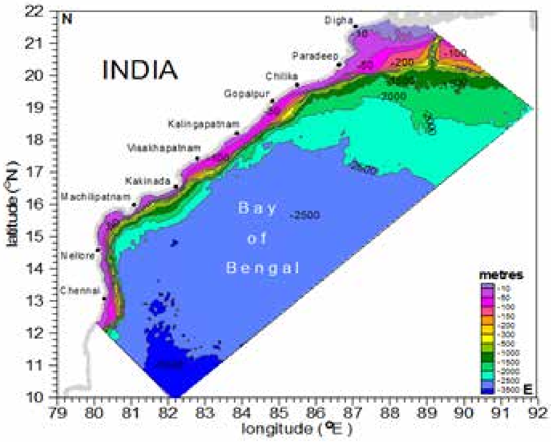

Figure 1: The model domain and bathymetry in contours.

The model bathymetry is derived from Earth TOPOgraphy 2 min (ETOPO2) data that has been modified by Shindhu et al. 2007 for better representation in the shallow coastal regions. Initial density fields are computed from monthly climatology of temperature and salinity derived from World Ocean Atlas 2009 (WOA09). At the sea surface climatological wind stress is given as forcing derived from satellite data (QSCAT) (http://dss.ucar.edu/datasets/ds744.4/). Relaxation of temperature and salinity is given periodically at the sea surface, available from AVHRR and WOA09 respectively. The purpose of using relaxation at the surface is to provide a constraint on the ocean at the interface with the atmosphere, and compensate for possible model drift due to errors in the surface heat and momentum fluxes (Ravichandran et al. 2013). Orlanski boundary condition (Orlanski, 1975) is applied at the open boundaries which allow any disturbance generated in the domain to pass through the boundary without significant distortion. We made use of the bilinear interpolation to generate the input data at the model grid points.

Results and Discussion:

Numerical experiments are carried out to study the circulation, density stratifications, etc. for all the months separately. The simulation is continued for 30 days in which the model achieves a steady state by 10 days and the rest 20 days are used for analysis. The surface circulation pattern and vertical temperature for analysis are five days averaged. For validation of simulated currents, a climatology of nine years of Ocean Surface Current Analysis - Realtime (OSCAR) currents derived from scatterometer and satellite altimeter data (http://www.oscar.noaa.gov/) is used. The vertical temperature at cross-sections are validated with a climatology of four years of available Array for Realtime Geostrophic Oceanography (ARGO) data (http://las.incois.gov.in/las/UI.vm) and is then interpolated to our model grid points.

The circulation features for pre-monsoon, summer monsoon and winter monsoon represented by April, July and December respectively are shown in the fig. 2. The model simulation (fig. 2a) is compared with the OSCAR currents (fig. 2b) for April. The simulated north-eastward EICC is in good agreement qualitatively with the OSCAR data all along the coast. A cyclonic gyre off Visakhapatnam in the deep ocean is also well simulated.

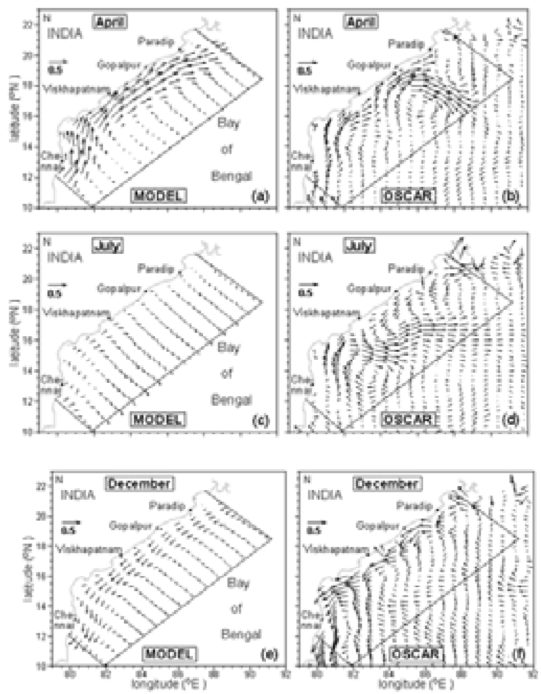

Figure 2: Left panel: (a,c,e) simulated sea surface currents for April, July and December. Right panel: (b,d,f) observed OSCAR currents for respective months.

During July which is a representative of monsoon season, the current in the south of the domain is northerly along the coast and southerly in the north of the domain (fig. 2c). However, the simulated currents along the coast are weak compared to the observed ones (fig. 2d). A pronounce southward current is seen up to Visakhapatnam in the observations whilst, this current is limited to Gopalpur in the simulations. This may be due to limitations of the northern open boundary condition that is supposed to take care of the southward freshwater flow entering into the domain. The simulations can be further improved provided freshwater flux based on the observations is prescribed through the boundary condition. During December, representative month of winter monsoon, the simulated currents are southerly tied to the coast (fig. 2e) and observations (fig. 2f). The north-easterly winds during this season produces southerly current. The reversal of the simulated currents are in good agreement with observations.

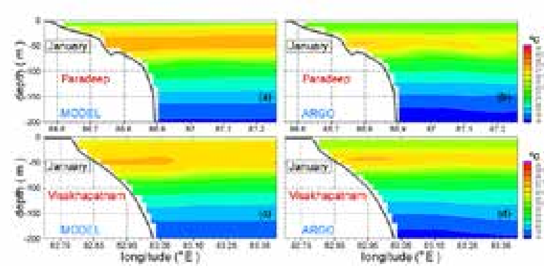

Figure 3: Left panel: (a,c) simulated vertical temperature. Right panel: (b,d) observed ARGO climatology for comparison off Paradeep and Visakhapatnam for January.

The vertical temperature off Paradeep (fig. 3a,b) and Vi-

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sakhapatnam (fig. 3c,d) are shown for January in which coastal processes like temperature inversions are simulated. As mentioned in the introduction, seasonal cooling during winter months traps high-temperature water at the subsurface. The TI is calculated as the difference in temperature between the surface and the high temperature water below. In January, it is noticed nearly 2.5°C and 2°C inversion off Paradeep and Visakhapatnam respectively in the simulations which is also observed in the ARGO climatology.

Summary:

The model simulated the EICC which is northward during pre-monsoon and the southward WBC during NE monsoon very well. Several kinds of eddies are seen during these seasons in both observations and simulations. During the monsoon season a lot of freshwater from the adjacent river system changes continuously the dynamics of the region which are to be incorporated for a better near-shore circulation. Temperature inversions are simulated comparatively well in the northern part at the cross-sections of Visakhapatnam and Paradeep during winter that fades away with the season. An accurate fresh water flux which leads to the occurrence of this process is required to the model for better simulations in future.

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