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Redistribution of low-salinity pools off east coast of India during southwest monsoon season

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ABSTRACT

The east coast of India receives significant inputs of fresh water into the Bay of Bengal during the southwest monsoon in comparison with the lower influx seen on the west coast. However, *in situ* observations made off the east coast suggest that in some years low-salinity pools appear offshore, as opposed to where the river discharge actually takes place. To date, no studies have offered any plausible reason for this anomaly. In an attempt to understand the processes involved, we used numerical modelling to elucidate the causes and mechanisms underlying the appearance of offshore low salinity pools. The model uses temperature and salinity information from the World Ocean Atlas 2001 as initial conditions, and is forced using wind stress derived from the weekly wind for July 2002 and 2010 from the NCEP FNL Operational Global Analysis, because of the need to validate the model using more recent observations. It was found that the formation of a low-salinity pool to the south of 16°N and its migration to an offshore region is a result of (i) coastal orientation, (ii) surface circulation supported by a weak East India Coastal Current that redistributes fresh water from two rivers, the Krishna and Godavari, and (iii) an influx of low salinity from the much larger river system to the north, resulting in anomalous pool(s) of low-salinity waters away from the coast. These findings are corroborated by CTD data, ARGO data, and Ocean Surface Current Analysis Real-Time currents.

1. Introduction

The Indian Ocean differs from the Atlantic and the Pacific in its limited northward extent to only 25°N. With its unique exposure to the monsoons, it represents an area of marked seasonal variability. The essential parts of the North Indian Ocean (NIO) are the Arabian Sea in the west and the Bay of Bengal (BoB) in the east. Although, the two are bound by nearly the same latitudes, they have very distinct basic characteristics. The BoB has significantly low-salinities because all major rivers in India discharge here and consequently, is distinguished by strong near-surface stratification. The seasonally reversing winds, together with the freshwater gain during the SW monsoon and the intense air-sea interaction, particularly; during the depression or cyclone development stages, make up the basic physical forcing that brings about large spatial and temporal variations of the surface waters that regulate the upper ocean circulation and the ensuing temperature and salinity fields. Differential distribution of salinity and temperature induce horizontal pressure gradients that alter the circulation. The Arabian Sea, on the other hand, is an area of high evaporation that receives little freshwater from the continental land mass and hence, is more saline.

The wind stress has a direct bearing on the upper layers of the ocean. It is, therefore, pertinent here to have an overview of the wind field, the physical processes, and circulation during the pre-monsoon and monsoon months, essentially because the wind systems are very similar right through, although the ocean circulation patterns are different. From March to May, the wind picks up strength and becomes more southerly. The observed wind driven coastal surface current is northward. Earlier studies by Rao et al. (1986) and Rao and Rao (1989) discuss temperature, salinity, and alongshore current structures over the inner shelf off Visakhapatnam along the east coast of India. From May, the winds begin to blow from the SW over most of the NIO. Over the bay, the Ekman drift is essentially eastward. The direction remains the same from June through September, although it peaks in July. Coastal ocean circulation in the BoB during the pre-monsoon months follows the

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wind pattern because there is no significant freshwater flow. Rainfall exceeds evaporation during the monsoon and there is a freshwater influx from the river system over the bay and east coast of India. One of the unique features of the BoB is the different regions experiencing, upwelling and downwelling in different seasons along the coast, which has been reported by several researchers. Upwelling has been reported off Visakhapatnam (Murty and Varadachari, 1968) from February to May (Rao et al., 1986). The surface waters in the bay have low-salinity, and stratification in the upper layers is dominated by salinity gradients (Shetye et al., 1991b). Recent observations in the western bay (Shetye et al., 1991a, 1993, 1996) and the ship-drift information (Cutler and Swallow, 1984) show a distinct seasonal cycle of surface circulation. There is no evidence of upwelling north of 17°N, in spite of the local prevailing southwesterly upwelling favourable winds. The local absence of upwelling in the north is attributed to the southward flow of surface freshwater that suppresses the offshore Ekman transport expected in case of surface wind stress only (Johns et al., 1992). Thus, the seasonally reversing monsoon winds affect the BoB circulation significantly (Cutler and Swallow, 1984; Hastenrath and Greischar, 1989). The semi-enclosed nature of the bay with an enormous quantity of freshwater discharge from the head bay river system results in a very intricate and intriguing circulation in this region. The available data is not adequate to understand the circulation and its variability. Hence, modelling studies are necessary to supplement and substantiate the observations. As upwelling is a transient phenomenon on a time-scale of about 4–5 days (Bowden, 1983; Liu et al., 2012; Babu et al., 2008), it is interesting to study the evolution of the processes on a weekly scale. The oceanic circulation and the associated physical processes are quite complex and so are the modelling tools to study the same.

The river discharge of the SW monsoon remains in the northern BoB and surges southward along the east coast only during the northeast (NE) monsoon (Shetye et al., 1996). Therefore, understanding the distribution of freshwater plume in the BoB is a very important aspect of the NIO. As the Ganga-Brahmaputra low-salinity water cascades down along the coast, it may not be surprising that the plumes skirt the coast, thereby showing low-saline waters a little away from the coast. However, when the rivers discharge freshwater in their estuarine region, one intuitively expects low-salinity in the region of freshwater input closer to the coast than offshore. In contrast, the available *in situ* observations do not indicate the same. The outright explanation may be that the circulation around the river discharge must be strong and conducive to deport the freshwater offshore. The freshwater received by the bay in large amounts during the southwest monsoon through river discharges get redistributed and eventually mixed up, affecting the hydrography of the surrounding ocean. Similar features are observed along the east coast of India where two major rivers, Krishna (16.0°N, 81°E) and Govdavari (16.5°N, 82°E), release a large quantity of freshwater into the BoB but an anomalous LSP is observed offshore from the CTD data in certain years. This necessitates studying this novel feature of occurrence and migration of LSP in a more detailed systematic manner. Here one point which is worth noting is that the northern side of the model domain is dominated by tides of the order of 80–100 cm which has a very little effect on the southern side of the order of 15–30 cm (Rao et al., 2010). Hence, the effect of tide is not considered here in the present study.

The hypothesis for the formation of anomalous pool(s) of low-salinity waters away from the coast rather than at the river discharge points are (i) coastal orientation, (ii) the surface circulation supported by a weak East India Coastal Current which redistributes the freshwater from the two rivers, Krishna and Godavari, and (iii) the low-salinity influx from the huge river system from the north which is established in the present study and the experiments are designed in such a way that the results would unequivocally establish the facts given in support of the distribution of freshwater discharge from two perennial rivers, Krishna and Godavari, into the BoB on the east coast of India during the southwest monsoon. The analysis region, salinity distribution and *in situ* observations during southwest monsoon are shown here for completeness of the present study. The following section describes the detailed model and experimental set-up and methodology adopted and then discussion of results and analysis and finally conclusions.

2(i) Model set-up and input fields

(a) Model Domain: Princeton Ocean Model (POM) has been implemented and configured on a curvilinear orthogonal grid to study the variability in circulation and salinity distribution off the east coast of India for August 2002 and 2010 (Blumberg and Mellor (1987) and Ezer and Mellor (1994)). The analysis area of the model extends from approximately 9°N to 22°N of the east coast of India, covering an alongshore extent of about 1200 km. The breadth of the region (distance from the coastline to the eastern open sea boundary) is about 500 km, approximately parallel to the coast as shown in Fig. 1 which shows the model domain and bathymetry.

(b) Horizontal and vertical resolution: The model incorporates a higher resolution near the coast, and in the vertical, a terrain-following sigma coordinate is used, having finer resolution near the surface and bottom and relatively coarse resolution in the middle. There are 200 (east-west) $\times$ 100 (north-south) grid points in the horizontal plane and 26 levels in the vertical, comprising 200 $\times$ 100 $\times$ 26 computational grid points. The resolution in the x-direction varies from 1.3 km to 3.7 km, finer near the coast. However, the resolution in the y-direction varies from 11.3 km to 13.8 km. The time steps are based on the CFL condition, according to

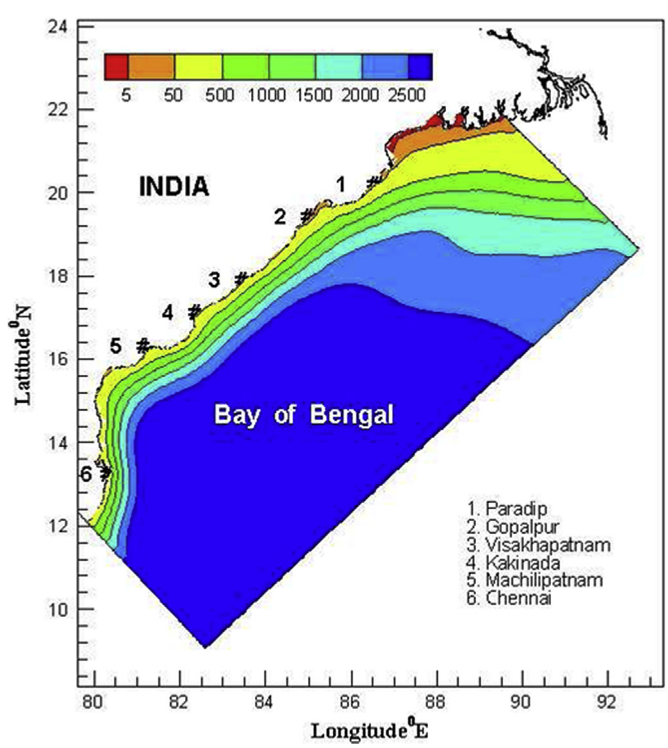

Fig. 1. Model domain and bathymetry (m).