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Observations of the sub-inertial, near-surface East India Coastal Current

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ABSTRACT

We present surface current measurements made using two pairs of HF (high-frequency) radars deployed on the east coast of India. The radar data, used in conjunction with data from acoustic Doppler current profiler (ADCP) measurements on the shelf and slope off the Indian east coast, confirm that the East India Coastal Current (EICC) flows poleward as a deep current during February–March. During the summer monsoon, when the EICC flows poleward, and October–December, when the EICC flows equatorward, the current is shallow (<40 m deep), except towards the northern end of the coast. Data from Argo floats confirm a shallow mixed layer that leads to a strong vertical shear off southeast India during October–December. A consequence of the strong stratification is that the upward propagation of phase evident in the ADCP data does not always extend to the surface. Even within the seasons, however, the poleward and equatorward flows show variability at periods of the order of 20–45 days, implying that the EICC direction is the same over the top ~100 m for short durations. The high spatial resolution of the HF radar data brings out features at scales shorter than those resolved by the altimeter and the high temporal resolution captures short bursts that are not captured in satellite-derived estimates of surface currents. The radar data show that the EICC, which is a boundary current, leaves a strong imprint on the current at the coast. Since the EICC is known to be affected significantly by remote forcing, this correlation between the boundary and nearshore current implies the need to use large-domain models even for simulating the nearshore current. Comparison with a simulation by a state-of-the-art Ocean General Circulation Model, run at a resolution of $0.1° \times 0.1°$, shows that the model is able to simulate only the low-frequency variability.

1. Introduction

The East India Coastal Current (EICC) is the boundary current at the western margin of the Bay of Bengal (hereafter often called BoB or just bay), the eastern wing of the North Indian Ocean (NIO). The seasonal cycle of the EICC has been described using data from ship drifts (Cutler and Swallow, 1984; Mariano et al., 1995) and hydrography (Shetye et al., 1991, 1993, 1996); excellent summaries of these observations are available (Shetye and Gouveia, 1998; Schott and McCreary, 2001; Mukherjee et al., 2014) and we provide but some details here.

The ship-drift and hydrographic data show that the EICC flows poleward near the surface during February–September and equatorward during November–January (Shetye et al., 1991, 1993, 1996). Though the southwesterly summer-monsoon (June–September) winds along the east coast of India are much stronger than the winds during the transition period in March–April between the winter (November–February) and summer monsoons, the poleward EICC is much stronger during this period of weak winds. Model studies of the climatological seasonal cycle show that this discrepancy between the strength of the EICC and the local wind forcing is due to the significant impact of remote forcing, which includes the effect of Ekman pumping in the interior of the bay, the winds blowing along the eastern boundary of the bay, and the winds over the equatorial Indian Ocean (EIO; (McCreary et al., 1993, 1996; Shankar et al., 1996; Vinayachandran et al., 1996)). This interplay between the locally (winds blowing along the east coasts of India and Sri Lanka) and remotely forced components determines the magnitude and direction of the EICC at the surface and at sub-surface levels. For example, an undercurrent has been identified during the summer monsoon (Shetye et al., 1991) and model studies suggest that it is forced remotely (McCreary et al., 1996; Vinayachandran et al., 1996). The data also suggest that the upsloping of isopycnals is restricted to shallower depths during the summer monsoon (Shetye et al., 1991) than during March–April, when the poleward EICC extends much deeper (Shetye et al., 1993); the equatorward EICC during the winter monsoon is also shallow (Shetye et al., 1996).

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Satellite altimeter data, which became available towards the end of 1992, allow the description to be extended beyond the seasonal climatology. The altimeter data confirm that the EICC forms the western-boundary current of a basin-scale seasonal gyre during March–April, but such a gyre is not evident during the summer monsoon (Eigenheer and Quadfasel, 2000; Shankar et al., 2002); this difference on the large scale had been suggested earlier on the basis of hydrographic data (Shetye et al., 1991, 1993) and satellite data of sea-surface temperature (Legeckis, 1987). Along-track altimeter data confirm the earlier ideas of the seasonal EICC and show that the cross-shore length scale varies from 60 to 150 km from north to south along the coast and that the interannual and intraseasonal EICC are comparable to the seasonal EICC (Durand et al., 2009). Unlike the seasonal EICC, however, the interannual and intraseasonal EICC are not coherent along the coast: they decorrelate along the coast. Eddy-like circulations, whose existence had been hinted at by Shetye et al. (1991), are seen in the altimeter data at both intraseasonal (Durand et al., 2009; Cheng et al., 2013) and interannual (Durand et al., 2009; Chen et al., 2012) periods in the regime of the EICC, which exhibits several meso-scale structures irrespective of the season (Kurien et al., 2010).

Prior to 2009, direct measurements of the EICC were few and were restricted to short durations; a summary of these measurements is given in Mukherjee et al. (2014), who present the data collected using ADCP (acoustic Doppler current profiler) moorings deployed on the continental slope off the Indian east coast under a programme on observing the boundary currents in the Indian Exclusive Economic Zone (EEZ). The ADCP data confirm the earlier findings regarding the seasonal reversal of the EICC, but show that the seasonal component is stronger than the intraseasonal component (Mukherjee et al., 2014), unlike for the West India Coastal Current (WICC), whose intraseasonal variability is comparable to or stronger than its seasonal cycle (Vialard et al., 2009; Amol et al., 2014). Striking in these ADCP data from the slope is upward propagation of phase, which is seen at both seasonal and intraseasonal time scales; on a few occasions, however, the phase propagates downward as well (Mukherjee et al., 2014; Amol et al., 2014).

The ADCP data from the east-coast shelf have not yet been described, unlike on the west coast (Amol et al., 2012, 2017; Amol, 2014), save for the near-inertial currents (Mukherjee et al., 2013). The shelf in the BoB is a data-sparse region and little is known about the circulation here. Shetye et al. (1991) showed a 40 km wide upwelling band hugging the shelf during the summer monsoon of July–August 1989 and pointed to the possible existence of shelf waves with an alongshore wavelength of 400–500 km, but there has been no confirmation of these observations using other data. Unfortunately, the altimeter data are not reliable in the vicinity of the coast and the narrow width of the east-coast shelf implies that even the along-track data of Durand et al. (2009) do not extend onto the continental shelf.

Though the ADCP data provide unprecedented information on the variability of the EICC, they suffer from three disadvantages. First, measurements on the shelf are restricted to the outer shelf as the threat to the moorings from fishing activity is considerable closer to the coast. Second, these are sub-surface moorings and the data are not available near the surface: the data lost owing to the echoes from the surface is roughly 10% of the range, which is around 40 m on the slope (Mukherjee et al., 2014; Amol et al., 2014) and 15–20 m on the shelf (Amol et al., 2012). Third, since the moorings are serviced once a year and do not include a surface buoy for real-time data transmission, the data are not available in real time.

One way to make continuous measurement of the surface current in near-real time is to use high-frequency (HF) coastal radars; since they are deployed on land, they are not threatened by fishing craft, unlike moored surface buoys deployed on the nearshore shelf. A pair of radars deployed on the coast can provide surface-current data at a temporal resolution of one hour and a spatial resolution of 6 km × 6 km over a patch of the sea spanning about 150 km × 150 km (Paduan and Washburn, 2013). In this paper, we use HF radar data for a few months during 2011–2012 from the northern and southern parts of the Indian east coast; these data are based on observations made using two pairs of HF radars deployed by the National Institute of Ocean Technology (NIOT), Chennai. Unfortunately, not much work has been done with these current data because of numerous gaps, which make it difficult to carry out analysis using standard tools. These gaps preclude, for example, the computation of a reliable spectrum using Fast Fourier Transforms (FFTs) or wavelets. While nothing can be done to fill the long gaps of the order of a month or more (unless the time scale of interest is much greater than the gap length), there are several shorter gaps of the order of a few days, which can be filled. Filling these short

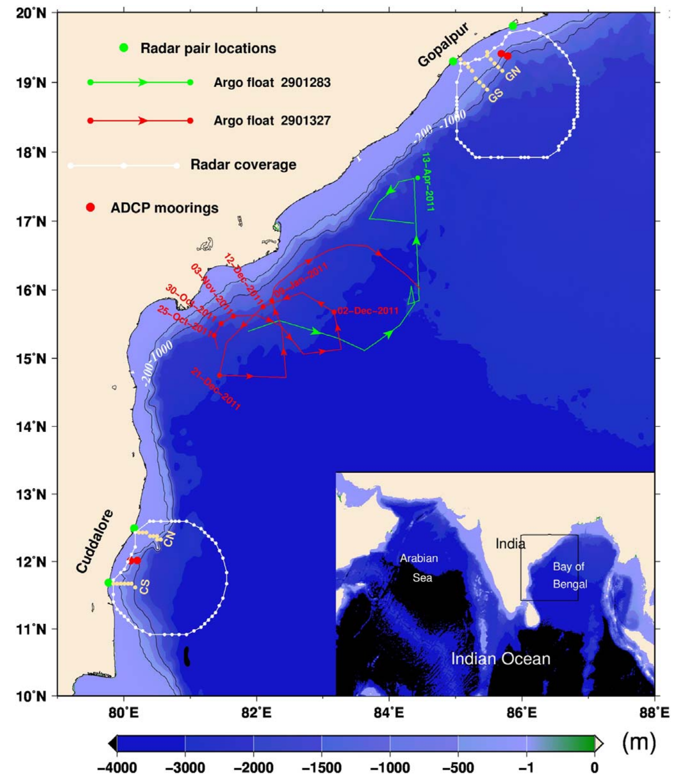

Fig. 1. The region of interest, the Bay of Bengal, and its location in the larger region (inset). The colour scale shows the bathymetry (metres). The 200 m (shelf break) and 1000 m contours are overlaid. The radar stations are depicted by the big solid green circles and the ADCP locations by the big solid red circles. The white curve with the soild white circles marks the limit of the radar coverage once GDOP (30–150° angle criterion; (Chapman et al., 1997)) is taken into account. The small solid yellow circles mark the cross-shore sections used to evaluate the cross-shore correlation of the surface EICC (Fig. 12); the correlation is estimated with respect to the location farthest from the coast, leading to an auto-correlation of 1 for this location. The tracks of the two Argo floats used to estimate the changes in the depth of the mixed layer are depicted by the green and red curves; the solid circles of the same colour mark the location at which the profile was selected. The profiles of temperature and salinity are plotted in Fig. 9 using the same colour as used here for the float trajectory.

Table 1
Location of HF radars used in this study and the period over which data are available from these radars. Though Odisha (Tamil Nadu) is the northern (southern) state in which the radars near Gopalpur and Puri (Cuddalore and Kalpakkam) are deployed, we use “Gopalpur” and “Cuddalore” to refer to the northern and southern radar pairs to match the nomenclature used for the ADCPs by Mukherjee et al. (2014). Data at Gopalpur (Cuddalore) are available for ~7 months (~5.5 months).

State	Towns	Location	Data period
Odisha	Puri Gopalpur	85.86°E, 19.80°N, 84.96°E, 19.30°N	23-August-2011 to 24-March-2012
Tamil Nadu	Cuddalore Kalpakkam	79.77°E, 11.68°N 80.15°E, 12.49°N	12-July-2011 to 30-December-2011

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