**VARIABILITY OF COASTAL CURRENTS IN THE BAY OF BENGAL DERIVED BY COMBINING SATELLITE ALTIMETRY AND DRIFTER OBSERVATIONS**

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**ABSTARCT**

The advent of satellite remote sensing have been enhanced our understanding of ocean circulation and variability. The present resoultion ofsatellite altimetry observations are enable to derive the coastal currents withfine spatial and temporal scales. By analysing the mean and seasonal velocity fileds of Bay of Bengal (BoB) between, the present study brings out some interesting features of mesoscale coastal circulation.High resoultion Eulerian velocity field is derived by combining the available satellite tracked surface drifter data with satellite altimetry and ocean surface winds. The drifter data used in this study includes Argos and surface drifter data from Global Drifter Program. The satellite altimeter data used are Maps of Sea Level Anomaly (MSLA) weekly files with a resolution of 1/3° in both Latitude and Longitude for the period 1993-2012. The weekly ocean surface mean wind fields derived from the scatterometers onboard ERS 1 / 2, Quikscat and ASCAT have been employed to estimate the wind-driven current. Mean velocity field displays northward flow along the eastern side with an average speed of 0.4 m/s in the northern part of the BoB and it feeds to the East Indian Coastal Current (EICC). Southward flowing (EICC) is the prominent current in the mean field and is visible from the head of the BoB as a narrow and strong southward flow along the eastern coast of India.The flow is intense between 12°N and 16°N, where the speed reaches 1 m/s. EICC shows strong temporal variations and strong mesoscale eddy activity in the western side.

**1. INTRODUCTION**

The Bay of Bengal is the northeastern arm of the Indian Ocean bordered by Sri Lanka and India on the west, Bangladesh on the north and Myanmar onthe east. The Andaman and Nicobar Islands along the eastern boundary separate the Bayfrom the adjacent Andaman Sea. The Bay receives inflows from many large rivers, which contain huge amounts of sediment, creating large fertile deltas, most notably along theIndian and Bangladesh coastlines and this is highly contributing to the water characteristics and stratification.

Bay of Bengal spans in the tropical monsoon belt and its environment is strongly affected by monsoons, storm surges and cyclones.The coastal circulation is subjected to seasonal reversal and inter-annual variability’s including lowfrequency planetary wave activity. Coastal currents are important because the coastal zone is the place where most nutrients, pollutants, and sediments are introduced into the ocean, and where most larvae are generated and dispersed. Coastal currents are responsible for the transport and dispersal of these biological, chemical, and geological tracers in the water.

Wyrtki (1971) presents preliminary information of Bay of Bengal waters.The seasonal variation of hydrography and circulation of BoB has been accounted in Varkey et al (1996). Main coastal current in the BoB is the western boundary current named as East Indian Coastal Current (EICC) in the BoB is identified using thermal infrared images of NOAA AVHRR (Legeckis, 1987) and is about 900km in length (Ratna Reddy et al. 1995), usually lying close to the coast but occasionally shifting offshore (Shetye et al., 1993) with an average speed of 30-55cm/s. There have been some hydrographic studies (Shetye et al., 1996; Stramma et al., 1996 and Sanilkumar et al., 1997) and numerical studies (McCreary et al., 1996; Shanker et al., 1996) further describing the western boundary current and its driving mechanisms.

The BoB exhibits seasonal reversing monsoon circulation along with depressions, severe cyclonic storms and comparatively low saline surface waters due to the large amount of river runoff from the Indian subcontinent. Strong surface circulations embedded with counter rotating gyres have been noticed (Poterma et al., 1991). The steadiness and strength of the gyres and currents in the BoB seems to depend on the development and latitudinal shift of the North Equatorial Current and the Monsoon Current (Varkey et al., 1996).

Comprehensive information on Bay of Bengal coastal circulation and processes is crucial for understanding its role in the oceanic and atmospheric processes. Knowledge of the coastal currents in BoB is still incomplete due tothe scarcity of in-situ observations.

Recent advances in satellite altimetry provide very accurate estimation of sea surface height, with highspatial and temporal resolution compared to with the in-situ observations. Satellite altimetry derived seasurface height data have been used to produce surface circulation and mesoscale features like fronts, eddiesand the vertical motions. Moreover, the time series of Sea surface height data is available even form end of1992, and it can be used for decadal scale variability studies. Considering the importance of Bay of Bengal, the present study will analyses the principle features of coastal currents in Bay of Bengal and the mesoscale features associated employing satellite and in-situ observations for the period 1993-2012 andinterpret the peculiarities of spatial and temporal variability in terms of the effects ofoceanographic and meteorological fields.

**2. DATA AND METHOD**

The surface drifter data used in this study comes from the Global Drifter Program (Surface Velocity Program), with the positions of freely drifting buoys located using the ARGOS satellite system. Data used were quality controlled and optimally interpolated to uniform six-hour interval trajectories using the drifters’ position data.

The satellite altimeter data used are Maps of Sea Level Anomaly (MSLA) produced by the Collect Localization Satellites (CLS), France. The Maps of Sea Level Anomaly were obtained by merging JASON/ TOPEX/POSEIDON and European Remote Sensing Satellites (ERS / Envisat) data using optimum interpolation. Maps were produced in every seven days interval since 1992 August with a resolution of 1/3° in both Latitude and Longitude are used. The weekly ocean surface mean wind fields derived from the scatterometersonboard ERS-1/2 QuikSCAT and ASCAT generated by CERSAT, France are used to estimate the wind driven current.

The instantaneous geostrophic velocity can be derived from the drifter observations, whereas the altimeter sea level anomalies provide the anomaly field. Hence, the mean velocity is calculated by subtracting the altimeter derived geostrophic velocity anomaly from the drifter-derived geostrophic velocity measured at the same time and location (Uchida & Imawaki, 2003; Benny et al.2014). This method estimates almost unbiased Eulerian mean velocities which are free from the sampling tendency of the drifters. Thus, the unknown mean velocity can be estimated for the grid box where a drifter had passed. The average of the calculated mean velocities in each grid, <Vmg (x)> gives a more accurate estimate by reducing the estimation error.

At a location x and time t, the instantaneous geostrophic velocity Vg(x, t) can be written as,

**Vg (x, t) = Vmg (x) + Vg’ (x, t), (1)**

Where,

Vmg (x) is the mean geostrophic velocity, and

Vg’ (x, t) is the geostrophic velocity anomaly

ie.,**Vmg (x) = Vg (x, t)** - **Vg’ (x, t) (2)**

The surface velocity has beenestimated from the drifter position data in each grid. The wind-produced slip iscorrected employing the relation given by Niller and Paduan (1995). An additional correction is made for drifters, which had lost its drogues during its traverse, using the empirical relation given by Pazan and Niller (2001). The Ekman velocity is estimated employing the Ralph and Niller (1999) model. The geostrophic velocity component is separated from the drifter velocity by subtracting the Ekman component.

The components of geostrophic velocity anomaly have been computed from altimeter sea level anomaly data using the conventional geostrophic relation.



**(3)**

**(4)**

Since the geostrophic approximation is not valid at the equator, the estimation of velocity anomaly is limited to 5° N towards equator in the present study. The instantaneous absolute geostrophic velocity is obtained by adding mean and instantaneous anomaly components.

**3. RESULTS AND DISCUSSION**

The Eulerian mean velocity field obtained by combining the satellite altimeter and drifter data reveals the details of coastal currents in BoB (mean). The altimeter derived velocity anomaly (anomaly) serves as a correction to the simple averages of the drifter-derived velocities (absolute). Although the large scale flow pattern is not much different from the simple average of drifter-derived velocities, the above mentioned correction by the altimeter-derived velocity anomaly shows significant differences along the peripherals and higher variations are found especially in the western part of BoB. Maximum anomaly of about 0.7m/s is found along the east coast of India, whereas, the eastern and northern BoB show comparatively weak (<0.3m/s) anomaly.

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Figure 1. Mean, anomaly and absolute velocity fields (m/s)

**3.1 Mean velocity field**

Southward flowing East Indian Coastal Current (EICC) along the western coast of the BoB is the prominent current in the mean field. This current is visible from the head of the BoB as a narrow and strong southward flow along the eastern coast of India up to south of Sri Lanka. The flow is intense between 12°N and 16°N, where the speed reaches 1 m/s and a confluence of current is observed at around 10°N, where zonal westward flows merges with the southward current. An anti-cyclonic eddy centred at 16.55°N, 86.95°E and a weak cyclonic eddy adjacent to it in north are the other prominent features in the western part.

The eastern BoB that includes Malacca Strait and Andaman Sea shows no organised circulation pattern in the mean field. But, traces of northward flow are visible along the eastern boundary. A strong anticyclonic eddy circulation is visible at the entrance of Malacca Strait north of Sumatra Island. South-westward flow occurs in the south-eastern end of BoB off Sumatra in the mean filed.In the northern part of the BoB northward flow prevails along the eastern side with an average speed of 0.4 m/s and it feeds to the EICC.

**3.2. Monthly coastal current pattern**

The monthly absolute velocities averaged over twenty years (1993 -2012) are presented in Fig. 2 to bring out the coastal circulation characteristics of the BoB.

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Figure 2. Monthly absolute velocities averaged over twenty years (m/s)

In January, strong southward flow of EICC along the east coast of India is observed from 17° N with higher speeds up to 1 m/s between 12° N and 15° N. The EICC has reversed in February and northward flow occupies most part off the east coast of India with a speed range of 0.2 to 0.4 m/s. However, traces of southward flow are visiblevery near to the coast. In March and April, this northward flow strengthened and the current speed reaches upto 0.6 m/s. This northward flow continues to the head of the bay. In May, the northward flow is weak and speed decreased to 0.4 m/s. Northward flow is further weakened and weak southward flow is occupies very near to the east coast and the head of the bayin June. During July and August, the southward flow close to the east coast is slightly strengthened but, northward flow still dominates away from the coast. In September, Southward flow prevails very near to the entire east coast and weak northward flow with a speed < 0.4m/s away from the coast.The southward flow of EICC is well developed even from head of the Bay along the east coast of India and intense flow exists between 8° N and 15° N in Octoberwith a maximum speed of 0.8 m/s. Southward flow reaches its maximum speed along the entire east coast in November with higher speed upto1 m/s between 5° N and 15° N. This strongcurrent flows southward along the east coast of Sri Lanka towards the equator.

Schott & McCreary (2001) also found that in late September, the EICC begins to flow southwards, and by November currents show southward flow everywhere along the east coasts of India and Sri Lanka.In December, the southward flow starts weakening at the head of the bay but it is still strong between 5° N and 16° N.Comparing to other parts of the BoB, the western region is subjected to strong seasonal reversals of wind-stress forcing. As a result, the EICC is the much affected current system in the BoB. The local winds have weaker effects on EICC variability. Indeed, remotely forced coastally trapped waves and Rossby waves crossing the interior of the BoB are major contributors to EICC variability (Schott & McCreary 2001).

The western-boundary confluence (Eigenheer & Quadfasel, 2000) identified near 10°N, with the EICC flowing northwards to the north of 10°N and southwards to the south is clearly visible in the maps. During January, at the peak of the winter monsoon before the winds begin to relax, the southward EICC decreases in strength and even reverses direction north of 15°N.From March to May, the poleward flowing EICC strengthens and extends southward to 10°N, even though the local winds are very weak. In our maps, the confluence is at 16°N in January and February and it is at 10°N from March to September.In October, November and December no current confluence is visible.

The flow is quite weak in the eastern side. A strong anticyclonic eddy exists at the entrance of Malacca Strait north of Sumatra Island.In January, northward flow is visible along the eastern boundary of the BoB between 16°N and 21°N and at the southern end. Irregular flow pattern is observed between 13° N and 16° N.In February and March similar situation exists with a slight increase in the speed (upto 0.6 m/s).In April the northward flow is organised but very weak and is clearly visible north of 15° N. Northward flow along the east coast in the northern part is strengthenedin May, which turns westward with speeds up to 0.6 m/s around the head of the Bob. Similar situation prevails till October with a slight increase in speed by August (0.8m/s).Northward flow prevailsalong the whole eastern boundary of the BoB during October. But, by November northward flow is weakened and irregular.

In addition to strong currents, BoB exhibits strong mesoscale eddy activity. In January an anticyclonic eddy centred at 87° E, 18° N in the western side and another one near the entrance of Malacca Strait also visible. The anticyclonic eddy observed (87° E, 18°N) is further strengthened in February with a speed of 0.7m/s at the western side. In March same situation persists. This anticyclonic eddy is at its maximum strength during April with a slight south eastward movement.In May, it begins to weakenandacyclonic eddy has developed on its north east side between 15° N and 20° N near the east coast of India. In June this cyclonic eddy gain its complete form with speed of 0.4m/s. InJuly,the anticyclonic eddy has completely disappeared and the cyclonic eddy is spatially enlarged.In August the cyclonic eddy started diffusing and by October it has completely disappeared. The strong anticyclonic eddy near the Malacca strait persists in all months at the same position. The cyclonic and anticyclonic eddies observed in July arealso consistent with the observations of Paul et al. (2009). A similar flow pattern is found along the western boundary and a cyclonic eddy has been reported from hydrographic data (Sanilkumar et al., 1997) and GEOSAT altimeter data (Babu et al., 2003).

**4. Conclusion**

The mean velocity field estimated by combining the satellite altimetry and drifter observations illustrates the coastal currents in BoB and brings out the details of magnitude of various currents and variability. The major coastal current observed in the mean field is western boundary EICC. The EICC is the strongest current in the BoB and its mean speed even reaches above 0.7 m/s. The EICC shows strong temporal variation. EICC is southward near the coast from July to January (strongest in October) and northward from February to June (Strongest in April). A western boundary confluence of zonal and coastal current is observed at around 10° N except in October, November and December.Weak northward flow exists along the eastern side of the Bay and is clearly visible north of 15° N. Besides strong currents, the BoB exhibits strong mesoscale eddy activity in the western side. The anticyclonic eddy observed (87° E, 18°N) disappears by July and instead a cyclonic eddy develops on its north east side between 15° N and 20° N near the east coast of India. Another anticyclonic eddy near the Malacca strait is strong and it persists in all months at the same location without much variation.

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**6. REFERENCES**

Babu, M. T, Y. V. B. Sarma, V. S. N. Murty, and P. Vethamony (2003), On the circulation in the BoB during Northern spring inter-monsoon (March-April 1987),Deep Sea Res., Part II,50:855-865.

Benny, N. P., A. Daisuke, K. R. Mridula, S.Sahrum, K. M. Omar, and M. Razali (2014), Mean and Seasonal circulation of the south Indian Ocean estimated by combining Satellite altimetry and surface drifter observations, Terr. Atmos. Ocean. Sci. Journal (Accepted).

Eigenheer, A., and D. Quadfasel. (2000), Seasonal variability of the BoB-of-Bengal circulation inferred from TOPEX/Poseidon altimetry, *J. Geophys. Res*., 105, pp. 3243-3252.

Legeckis, R., (1987). Satellite observations of a western boundary current in the Bay of Bengal. J. Geophys. Res., 92, pp. 12974-12978.

McCreary, J. P., Han, W., Shanker, D., and Shetye, S. R., (1996). Dynamics of the East India Coastal Current: 2. Numerical simulations. J. Geophys. Res., 101, pp. 13993-14010.

Niiler, P. P. and D. Paduan (1995), Wind-driven motions in the northeast Pacific as measured by Lagrangian drifters*,* J. Phys. Oceanogr., 25, pp. 2819-2830.

Pazan, S. E., and P. P. Niiler (2001), Recovery of near surface velocity from undrogued drifters, J. Atmos. Oceanic Technol., 18, pp. 476-479.

Paul, S., A. Chakraborty, P. C. Pandey, S. Basu, S. K. Satsangi, and M. Ravichandran, (2009), Numerical Simulation of BoB Circulation Features from Ocean General Circulation Model, Mar. Geod., vol 32,DOI: 10.1080/01490410802661930

.Poterma, J. T., Luther, M. E., and O’Brien, J. J., (1991).The seasonal circulation of the upper ocean in the Bay of Bengal. J. Geophys. Res., 96, pp. 12667-12683.

Ralph, A. E and P. P. Niiler (1999), Wind-driven currents in the tropical Pacific, J. Phys.Oceanogr., 29, pp. 2121-2129 .

Ratna Reddy, S., A.K. Easton, S.R. Clarke, A. Narendra Nath, and M.V., Rao, (1995) Gyres off Somali coast and western boundary currents in the Bay of Bengal during the south-west monsoon,  Int. J. Remote Sens., 16(9), pp.  1679–1684.

Sanilkumar, K. V., Kuruvilla, T. V., Jogendranath, D. and Rao, R. R. (1997).Observations of the Western Boundary Current of the Bay of Bengal from hydrographic survey during March 1993. Deep-Sea Res., I, 44, pp. 135-145

Shankar, D., McCreary, J.P., Han, W. and Shetye, S.R. (1996). Dynamics of the East India Coastal Current: 1.

Schott, F.A, and J.P. McCreary, (2001), The monsoon circulation of the Indian Ocean, Prog, in Oceanog., 51, pp. 1-123.

Analytic solutions forced by interior Ekman pumping and local alongshore winds. Journal of Geophysical Research 101: doi: 10.1029/96JC00559. issn: 0148-0227.

Shetye, S. R., Gouviea, A. D., Shenoi, S. S. C., Sunder D., Michael, G. S. and Nampoothiri G.(1993). The western boundary current of the seasonal subtropical gyre in the Bay of Bengal. J. Geophys. Res., 98, pp. 945-954.

Shetye, S. R., & Gouviea, A. D., Shanker, D., Shenoi, S. S. C., Vinayachandran P, N., Sunder D., Michael, G. S. and Nampoothiri G.(1996). Hydrography and circulation in the western Bay of Bengal during northeast monsoon. J. Geophys. Res., 101, pp. 14011- 14025.

Stramma, L., Fischer, J. and Schott, F. (1996).The flow field off southwest India at 8°N during the southwest monsoon of August 1993. J. Mar. res., 54, pp. 55-72.

Uchida, H., and S. Imawaki, (2003), Eulerian mean surface velocity field derived by combiningdrifter and satellite altimeter data, Geophys. Res. Lett., Vol. 30 (5),1229,DOI:10.1029/2002GLO16445.

Varkey, M. J., Murty, V. S. N. and Suryaanarayana, A.(1996). Physical Oceanography of the Bay of Bengal and Andaman Sea. Oceanogr. And Mar. Biology: an annual review, 34, pp. 1-70.

Wyrtki, K. (1971), Oceanographic Atlas of the International Indian Ocean Expedition, National Science Foundation, Washington D.C., 531.