Indian Journal of Geo-Marine Sciences
Vol. 39(4), December 2010, pp. 489-496

Intra-seasonal variability of the coastal currents around India: A review of the evidences from new observations

S S C Shenoi

Indian National Centre for Ocean Information Services, Hyderabad 500 055, India
[E-mail: shenoi@incois.gov.in]

Received 20 August 2010, revised 21 December 2010

The seasonal cycle of the coastal currents along the Indian coast and their dynamics is well known. Till recently, it was believed that the seasonal signal dominates the coastal currents due the seasonal reversals of monsoonal winds. But the recent studies using satellite based altimeter and *in situ* measurements using moored instruments provided evidences on the importance of intra and interannual variabilities embedded in them. This article reviews the evidences available from these observations.

[**Keywords:** Arabian Sea, Indian Ocean, Coastal Kelvin waves, Monsoon, *In-situ* measurements]

Introduction

The North Indian Ocean is a very special ocean. It is not connected to the poles, it is tropical, it has very strong seasonal forcing, with the total reversal of winds and dramatic current reversal. In response to the annually reversing monsoon winds the major currents in the Indian Ocean also undergo variations on semi-annual and annual time scales. This makes the surface circulation in the Indian Ocean unique compared to that in Atlantic and Pacific. The seasonality is more prominent in the north than in the south.

Earlier observations obtained from hydrography[1], ship drifts[2] and the satellite tracked drifters[3] established the picture of the seasonal cycle. According to Shenoi *et al.*[3], the South Equatorial Current that flows towards west between 10 - 20° S and the equatorward East Africa Coastal Current are the only currents in the Indian Ocean that does not undergo the reversal in direction. The hydrographic observations reported by Shetye *et al.*[4-8] re-established the picture of seasonal cycle for the coastal currents around India. On the basis of hydrographic observations Shetye *et al.*[4] suggested that the circulation off the west coast of India during the summer monsoon (June – September) is weak, but dynamically similar to the wind-driven eastern boundary current. During this period, the transport of the equatorward current increased from less than 0.5×10^6 m^3 s^{-1} to about 4×10^6 m^3 s^{-1} from north to the southern end of the coast. However, during the winter monsoon (November – February) the poleward current along the coast flowed against the prevailing winds. In the absence of any proven theoretical frame work, they proposed a driving mechanism based on the longshore pressure gradient[5]. In the north, at about 22° N, the flow was restricted mainly to the vicinity of the continental slope; the current was narrow (100 km), 400 m deep jet with a transport of 7.0×10^6 m^3 s^{-1}. This was a surprise. Similarly, the hydrographic observations along the east coast threw another surprise. The East India Coastal Current (EICC) is best developed during March-May, when winds in the region are very weak, in fact, weakest of the year[6]. This strong western boundary current of seasonal subtropical gyre, seen during March-May, was attributed to Ekman pumping in the interior Bay of Bengal similar to that with the classical subtropical gyres of the Atlantic and Pacific Oceans. During the summer monsoon, like the WICC, the EICC is much weaker and unorganised than in the winter monsoon when it can be traced all along the east coast using salinity as a tracer. Shetye *et al.*[7] had attributed this shallow poleward EICC to the local alongshore winds. During the winter monsoon the EICC carries the low-salinity waters that originate in the northern bay due to river runoff[8]. The EICC transports these freshwaters all the way to the southwest coast of India after turning around Sri Lanka. From there, the WICC carries it northward along the coast. During this season, the EICC and WICC together girdle the coast forming a continuous flow from the northern Bay of Bengal to the northern Arabian Sea. This is the only time the coastal circulation around India takes such a well developed character covering the entire coastline.

Hydrography and altimetry showed that a “high” in surface topography forms off southwest India in winter monsoon and that a "low" forms during the summer monsoon[9-11]; the high and low, called Lakshadweep high/low due to its proximity to the Lakshadweep group of islands[12]. The high/low propagates westward and extends across the southern Arabian Sea a few months after genesis. The schematic in Figure 1 depicts the seasonal currents in the north Indian Ocean, in particular the coastal currents around India.

It is obvious that the circulation described above cannot be forced by local winds alone because, at times, the currents flow in directions opposite to winds. So what drives the currents along the Indian coasts? Luckily, some of the theoretical studies emerged out since early nineties helped in evolving the necessary theoretical framework to explain the large-scale seasonal circulation in the north Indian Ocean in general and the coastal currents around India in particular[13-15]. According to this framework, the coastal currents around India form an integral part of the circulation that encompasses the entire north Indian Ocean basin.

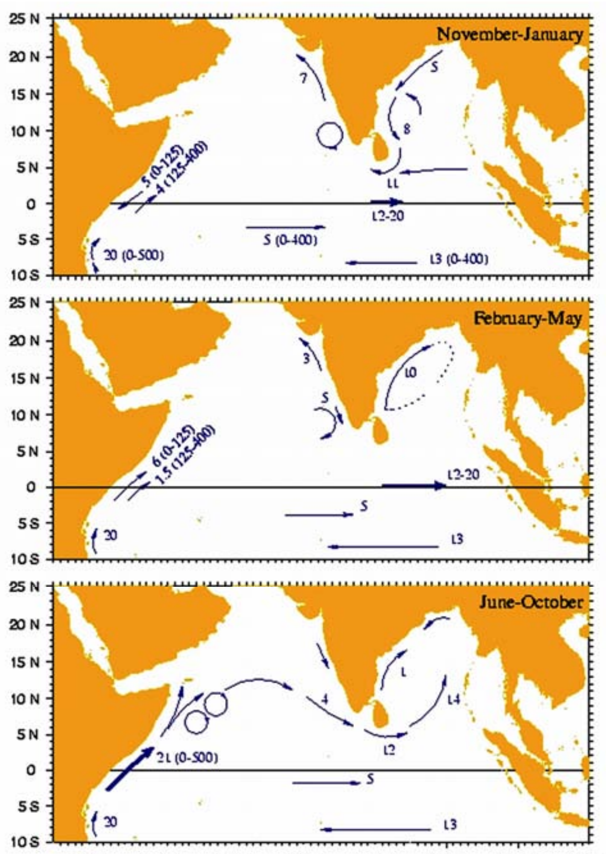

Fig. 1— The schematic of the seasonal cycle of surface currents in the north Indian Ocean. The numbers along the arrows indicate the transports in Sverdrups (1 Sverdrup = 1.0 x 10^6 m^3s^{-1}). The numbers in parenthesis indicate the depth of water column over which the transports were estimated (Curtsy D. Shankar).

Hence, to understand the coastal currents, it is necessary to look at the entire basin. This framework basically looked at the surface currents as a consequence of wind-forced and free coastally and equatorially trapped Kelvin and Rossby waves. Three mechanisms can independently or combined trigger these waves: (i) the coastal winds that generate the coastal Kelvin waves that travel long distances influencing the circulation remotely. These waves when propagate along the eastern boundary of the basin, radiate westward propagating Rossby waves influencing the circulation in the open sea. This mechanism was first pointed out by Mc Creary *et al.*[13], (ii) the winds along the equator that trigger the Kelvin waves along the equator. Yu *et al.*[14] and Poterma *et al.*[15] suggested that these equatorial Kelvin waves when arrive on the coast of Sumatra in the east generate coastal Kelvin waves that move along the periphery of the Bay of Bengal. As they propagate northward, they also radiate Rossby waves that influence the circulation in the open bay. (iii) the divergence of Ekman transport over the open sea regime of the north Indian Ocean that trigger the Rossby waves that influence the open sea circulation[6].

Shankar *et al.*[16] and Mc Creary *et al.*[17] have examined the contribution of each of the three forcing mechanisms to the driving of the EICC. They concluded that the strong northeastward flow during March-April results from a combination of all three forcing functions, whereas the weaker northeastward flow during June-September is primarily the result of local winds and the southward EICC during October-January is forced by Ekman pumping and the local alongshore winds. On the contrary, the WICC is mainly forced remotely by Kelvin waves that reach the west coast from Bay of Bengal[13]. In other words, the winds along the periphery of Bay of Bengal that trigger the coastal Kelvin waves as well as the winds at the equator that triggers the Kelvin waves are more important in determining the circulation along the west coast of India rather than the local winds itself.

Shankar and Shetye[12] carried this idea further to propose that these Kelvin waves are also responsible for the formation of Lakshadweep High/Low. They argued that high/low arise when annual and semi-annual Kelvin waves radiate Rossby waves while propagating northward along the west coast of India. Later Shenoi *et al.*[11,18,19] highlighted the active role played by this high/low on the genesis, growth and decay of warm pool that develops in the region.

Shankar *et al.*[20] assembled data on ship drifts, winds and Ekman drift, and geostrophic currents derived from altimetry and hydrography to describe the climatological seasonal cycle of the monsoon currents. They have used an oceanic general circulation model to simulate these currents and estimate their transports and also used a 1½ -layer reduced-gravity model to investigate the processes that force them. They concluded that the monsoon currents extend over the entire basin, from the Somali coast to the eastern Bay of Bengal though they do not come into being, or decay, over this entire region at a given time. Different parts of the currents form at different times, and it is only in their mature phase that the currents exist as trans-basin flows.

Though so much is known about the seasonal cycle of the coastal currents around India, due to the lack of observations, not much attention was paid to the variation in coastal currents at sub-seasonal time scales till recently. The winds over the Indian Ocean are known to possess intraseasonal frequencies[21]. In particular, the Madden-Julian Oscillation[21] has energetic fluctuations of surface winds in the 30 – 80 day range[23]. The new observational records of upper ocean currents and sea levels, however, show the dominance of intraseasonal variations of alongshore currents. This manuscript reviews some of the reports emerged from new observations and advocates the need for an integrated coastal observation system around India.

Spatial and temporal variability of East India Coastal Current

The hydrographic observations[6-8,24-25] and ship-drifts[2,26] helped in painting a clear picture of seasonality in EICC. The surface drifter trajectoies[3] as well as the eddy-resolving numerical models[26] also concurred with the picture that emerged from hydrographic observations and ship-drifts. All these showed a strong spatially correlated EICC during March-April, a weak spatially decorrelated EICC during the summer monsoon and a moderate, but spatially correlated EICC during the winter monsoon. During the summer monsoon, the EICC was discontinuous due to the presence of meso-scale eddies[7]. Even during other two seasons also, the EICC was embedded with several mesoscale structures. The meso-scale eddies and structures embedded in the EICC indicate that the finer picture is much more complicated than the gross picture of EICC. However, for the lack of observations, we did not know that the finer spatial structures and the intraseasonal oscillations with periods starting from 10 to 100 days are as important as the seasonal ones in determining the circulation along the coast of India.

For the want of suitable data sets that can be used to study the spatiotemporal structure of EICC, Durant *et al*.[28] have used a high resolution data set prepared based on satellite altimetry. Though the altimetric sea levels are available for last one decade in the form of standard girded products, they proved to be too coarse to capture the spatiotemporal structure of EICC. The standard altimetric products also suffered from heavy loss of data near the coast due to large errors within the boundary regime of EICC[29-30].

The major problems of altimetry in the shelf areas arise from data accuracy due to the lack of standard geophysical corrections (tidal and de-aliasing of high-frequency barotopic motions) and the data gaps near the coast. Due to these reasons, usually, the near-coastal data are often flagged out in standard girded products. However, the careful analysis of measurements and the corrective terms allowed the recovery of valid measurements in the coastal regions[31]. Hence, Durand *et al*.[28] used a data set prepared, recently, by Briol *et al*.[32] to analyse the spatiotemporal structure of EICC. The studies showed that the reprocessed new data set is useful to study the spatiotemporal structure of EICC[30]. The new data set resolved timescales ranging from a few months to a few years, and the high along-track resolution yielded the description of the cross-shore structure of the current.

The altimetric tracks selected by Durand *et al*.[28] for the study of spatiotemporal variability of EICC is given in Figure 2. As expected, the seasonal cycle dominates the variability (Figure 3), but the non-seasonal timescales have similar energy levels all along the EICC path. In contrast to the seasonal cycle, the interannual and intraseasonal components are decorrelated along the coast (Table 1). The non-seasonal timescales possessed as much energy as the seasonal currents all along the EICC path. The year-to-year variability also is considerable, taking the form of short-lived (typical duration was a few weeks), intense (of order 1.0 m s^{-1}) bursts. The magnitude of these intraseasonal bursts does

Table 1— Correlation matrix of the alongshore component of EICC speed anomaly between the various points along the path of EICC[28]. See Figure 2 for location of points A-G. Correlations significant at 95% level are underlined.

Point	A	B	C	D	E	F
B	<u>0.32</u>					
C	<u>0.26</u>	<u>0.30</u>				
D	0.16	0.20	<u>0.27</u>			
E	0.13	0.23	<u>0.30</u>	<u>0.42</u>		
F	-0.07	<u>-0.26</u>	0.13	0.21	<u>0.29</u>	
G	-0.36	-0.20	-0.01	<u>0.44</u>	<u>0.33</u>	<u>0.49</u>

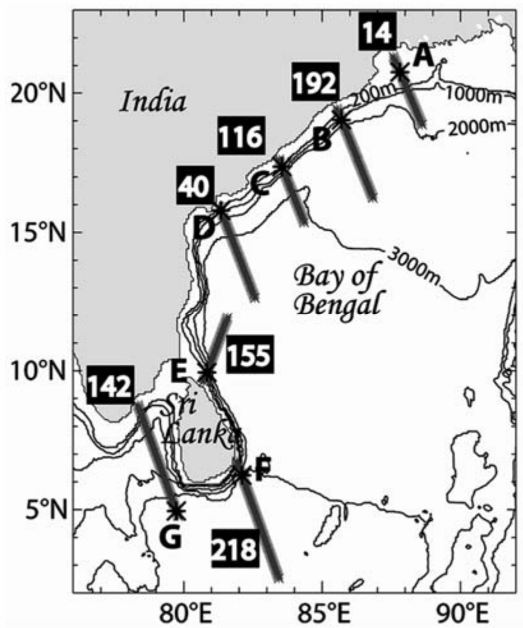

Fig. 2— The portions of Topex/Posidon altimetric tracks used for the study (thick grey lines). The Topex/Posidon track numbers are indicated in black squares. The points A, B, C, D, E, F, and G indicate the locations of the data user for the computation of Lomb periodograms shown in Figure 3. The 200 m, 1000 m, 2000 m, and 3000 m isobaths are also shown. (Figure reproduced from Durand *et al.*[28])

not seem to restrict the occurring to a particular season. The data set also revealed considerable year-to-year modulation of the seasonal cycle.

Decorrelated alongshore winds along the coast are identified as the possible cause for the decorrelation (discontinuity in the flow) of EICC at intraseasonal timescales. On the other hand, the Ekman pumping field over the bay is considered as the possible mechanism behind the decorrelation of interannual EICC. However, they did not investigate the role of other possible forcing mechanisms of the EICC (remote forcing by winds blowing along the eastern and northern boundaries of the bay and by the winds in the equatorial Indian Ocean).

Durand *et al.*[28] also revealed, for the first time, the typical cross-shore length scale of the EICC and its cross-shore structure (Figure 4). The typical cross-shore length scale of EICC increased from 60 km in the northern bay to 150 km south of Sri Lanka. This trapping scale is somewhat greater than but comparable to the Rossby radius of deformation. In the cross-shore direction, the current is highly correlated at all timescales and the EICC is trapped against the shelf with the current offshore flowing in the opposite direction at most locations.

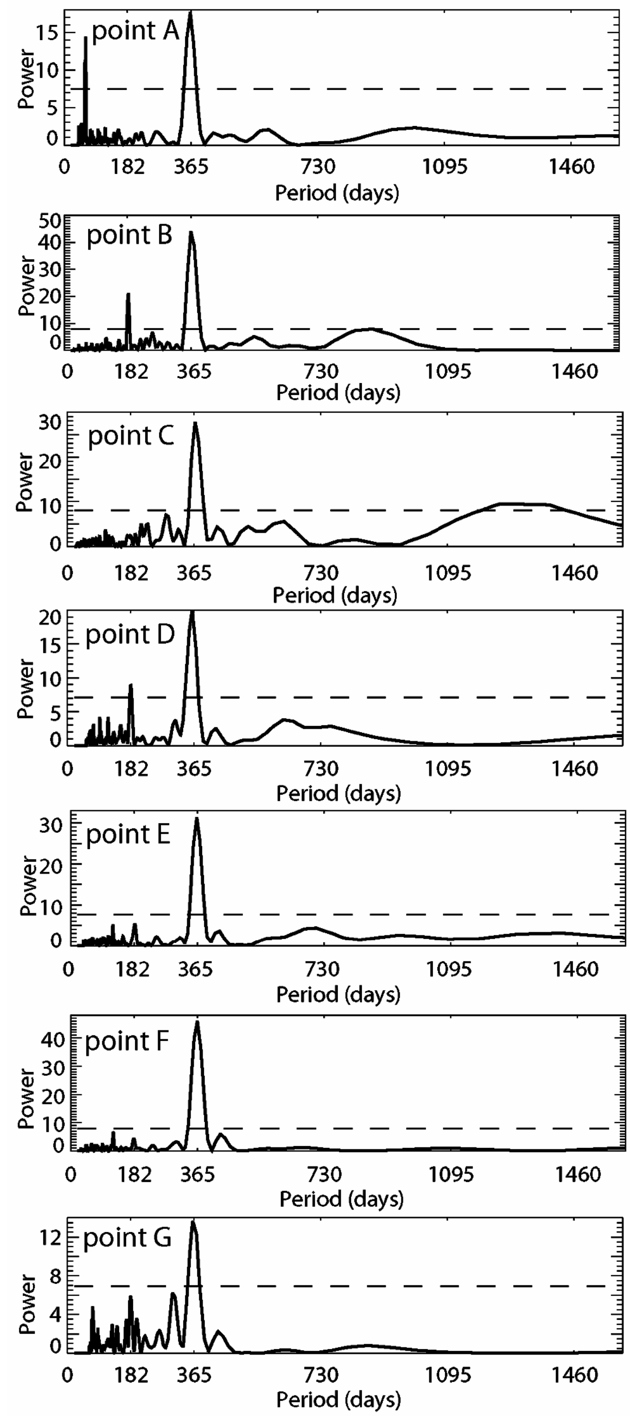

Fig. 3— Lomb periodograms of the cross-track geostrophic surface current anomaly for each EICC point shown in Figure 2. The 95% significance level is indicated by dashed lines. (Figure reproduced from Durand *et al.*[28]).

Intraseasonal variability of west India Coastal Current

The *in situ* measurements of currents over the shelf off Goa, depicted the presence of high frequency oscillations of WICC[33,34]. However, the duration of the time series were insufficient to capture the intraseasonal as well as the interannual variability of WICC. Recently, National Institute of Oceanography, Goa initiated the long term measurements of coastal currents around India with the support from Indian National Centre for Ocean Information Services/Ministry of Earth Sciences using moored Acoustic Doppler Current Profilers (ADCP). The locations of ADCP moorings deployed to measure the coastal currents around India are shown in Figure 5.

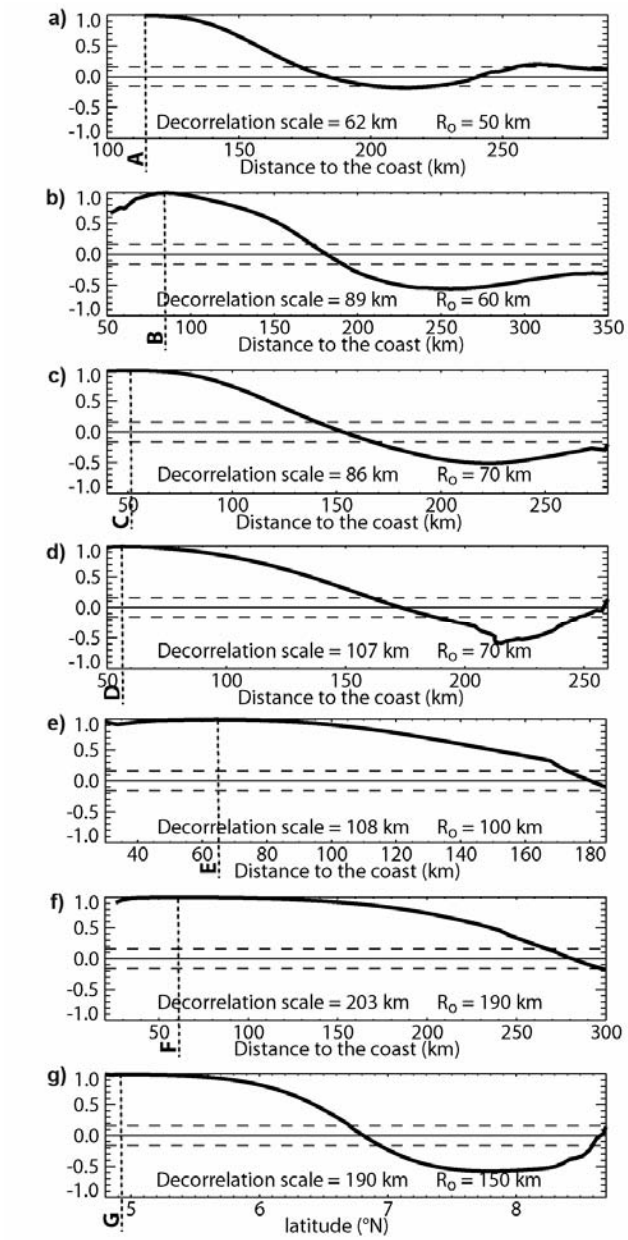

Fig. 4— Correlation along each altimetric track of the cross-track geostrophic current anomaly with the reference point (A-G) (Figure reproduced from Durand *et al*.[28]).

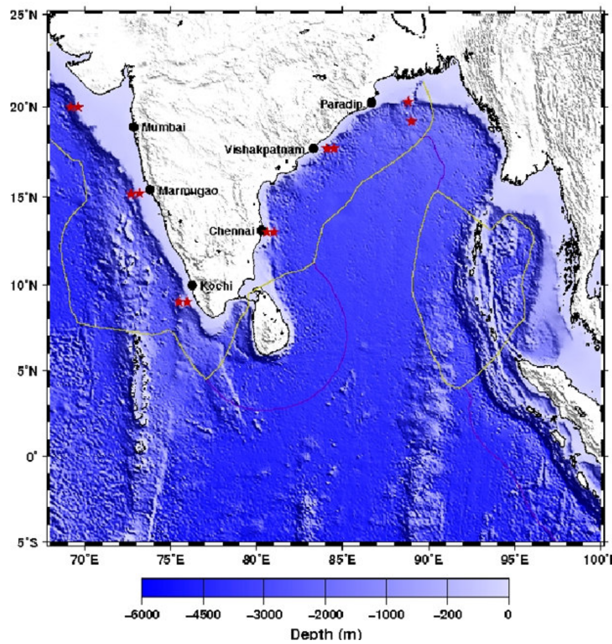

Fig. 5— Locations of ADCP moorings deployed around the Indian coast. At each location, two ADCPs were deployed one at the mid shelf (around 100 m water depth) and the other at the continental slope region (around 1200 m water depth).

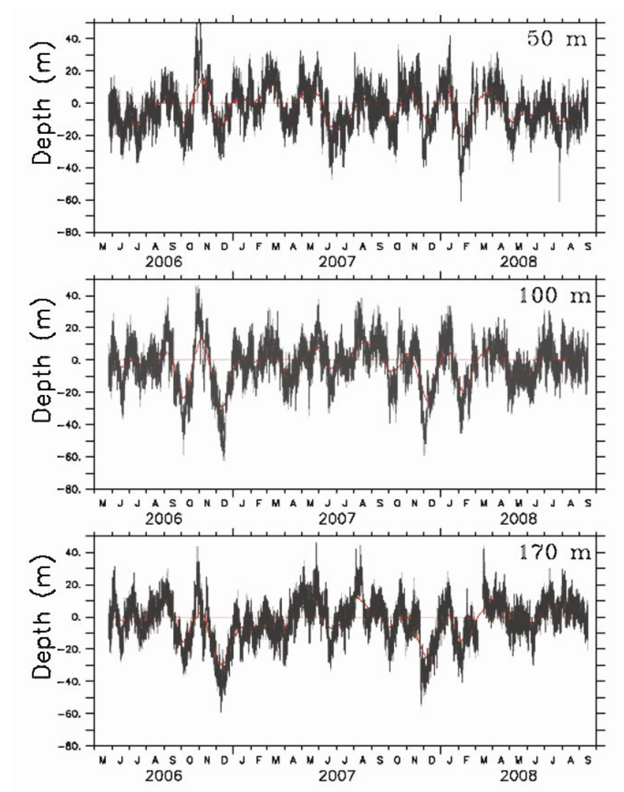

Fig. 6— Alongshore currents measured by ADCP at 50, 100 and 170 m off Goa at the slope region. The depth of water column at the location was about 1150 m.

The time series data from these moorings will become available soon on the recovery of the moorings. However, data from moorings off Goa, extending over 30 months, is now available. The analysis of the available time series clearly shows the dominance of intraseasonal variability of WICC (Figure 6). An upward-looking RDI 75 kHz Long-Ranger ADCP was deployed on a subsurface mooring (at 15° 09' N 72° 43' E) in a water column of 1150 m deep on the continental slope and another upward-looking RDI 300 kHz broad-band ADCP was deployed in 100 m deep water column on the mid shelf region off Goa. The ADCP sampled in high-resolution mode, recording ensemble pressure and velocity in 8-m bins at depths above the nominal ADCP location at 400 m. The intraseasonal variability, ranging from 30 to 120 days, seems to dominate the WICC at all levels including the poleward under current that develops during the summer monsoon season. The magnitudes of variability were similar on the mid shelf as well as at the slope region (Figure 7).

Vialard *et al.*[35] further analysed the time series obtained from the continental slope together with the time series of sea level obtained from satellite altimeters. They showed that seasonal variability of the currents is much weaker than the intraseasonal variability that peaks at 55-110 days band (Figure 8). The peak-to-peak variability of intraseasonal currents was as high as 40 cm s^{-1}. In contrast to the currents, the variations in sea level over the shelf, displayed a clear seasonal cycle with an abrupt sea-level rise in October – November and fall in June – July, coinciding with the arrival of the seasonal downwelling and upwelling coastal Kelvin waves[12]. The intraseasonal component of sea level at 55-110 days band, however, coincided mostly with the currents in the same band (Figure 8).

This observation raised two important questions, (i) why do the intraseasonal sea level and alongshore current variations tend to be in phase and (ii) why is the seasonal cycle so weak in the currents? Vialard *et al.*[34] explained this observation in the framework of linear theory.

At 15° N, the minimum period for planetary waves is ~ 90 days. Hence, the energy at intraseasonal frequency will largely gets trapped at the coast in the form of poleward-propagating Kelvin waves, while lower-frequency signals associated with the seasonal cycle radiates offshore as planetary waves. This dynamical difference results in a steeper offshore slope of sea level at intraseasonal timescales and thus stronger geostrophic alongshore currents near the coast. A consequence is that the alongshore currents are in-phase with intraseasonally filtered sea level near the coast. Further, the Madden-Julian Oscillations associated with the surface wind signals over the Northern Indian Ocean are suggested as the causative mechanisms of intraseasonal winds that force the Kelvin waves and hence the intraseasonal currents[34].

Summary

The new observations suggest that the EICC as well as the WICC possess energetic intraseasonal variability that is comparable to the seasonal cycle.

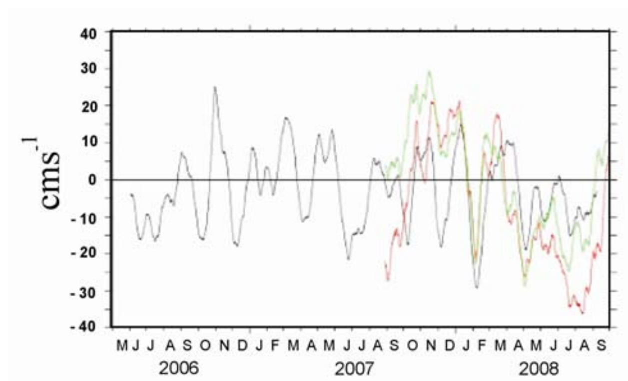

Fig. 7— Time series of alongshore currents measured using the ADCPs deployed off Goa on the shelf and slope. The black line indicates the alongshore currents at 50 m level at the slope region (depth of water column 1150 m). The red and green lines indicate the alongshore currents at 50 and 11 m levels on the shelf (depth of water column on the shelf was 100 m).

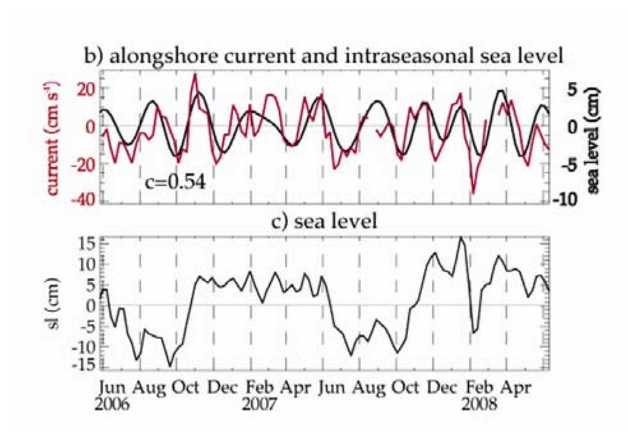

Fig. 8— Top panel shows the weekly averaged alongshore current at 50 m at the slope region off Goa (red curve) and the 55-110 days filtered sea level (black curve). Bottom panel shows the sea-level from altimeter (Figure reproduced from Vialard *et al.*[35]).

This changed the earlier perception that the currents in the north Indian Ocean and in particular the coastal currents around India are primarily seasonal associated with the reversing monsoonal winds. The EICC appears as an inherently discontinuous flow, taking the form of a few recirculating loops along the EICC path, with a typical cross-shore spatial scale of 150–200 km (Figure 9). The directions of the loops are highly variable at all timescales from intraseasonal to interannual. This discontinuity of the EICC in space and time implies that the basic pathways and advective timescales for the inter-basin exchange of water masses between the Bay of Bengal and the Arabian Sea are not robust when the full spatiotemporal variability of the EICC is considered.

In the WICC, the intraseasonal variability seems to exceed the seasonal cycle on the shelf and shelf break as the intraseasonal sea level gets trapped near the coast while the seasonal signal propagates further offshore. The new data from the ADCP moorings deployed along the coast will help in further enhancing our understanding of the spatiotemporal variability in the coastal currents around the Indian coast. The enhanced understanding of these major boundary currents will help in understanding their impact on the continental shelf environments, ecosystems and biodiversity. Similarly, it will also help in understanding the role of the oceans on monsoons as well on the climate. The effect of Indian Ocean on the continental climate-system at all time scales, from seasons to decades is yet to be seen.

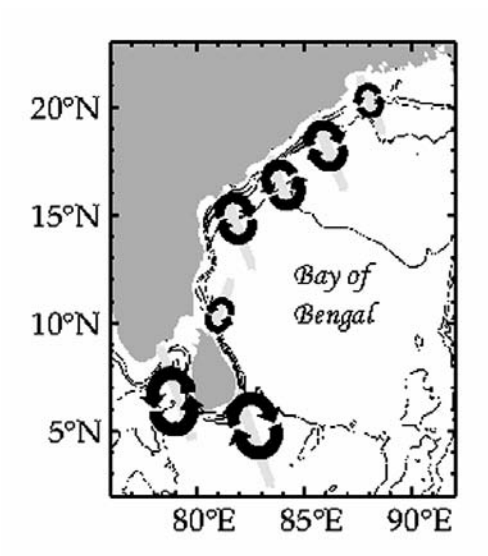

Fig. 9— Schematic of EICC circulation pathways. The recirculation cells are represented with arbitrary directions (Figure reproduced from Durand *et al.*[28]).

Given the extent and challenge of addressing the broad range of marine issues in the Indian EEZ, the new observations may be considered as the beginning of an integrated observation system that India needs; though the cost of an adequate observing system will be high due to the great length of coastline.

Acknowledgements

Drs. F. Durand, J. Vialard, D. Shankar and A. Prakash provided the figures in required formats. The efforts of V. Fernando and Y. Agavadekar in the deployment and maintenance of ADCP moorings around India are gratefully acknowledged.

References

1 Wyrtki K, *Oceanographic atlas of the international Indian Ocean expedition*, (U.S. Government printing office, Washington, D.C.) 1971, pp. 531.

2 Cutler A N & Swallow J C, *Surface currents of the Indian Ocean (to 25°S, 100°E): Compiled from historical data archived by the Meteorological Office*, Bracknell, UK, Rep. 187, (Inst. of Oceanogr. Sci., Wormley, U.K.) 1984, pp. 8.

3 Shenoi, S.S.C., Saji, P.K. & Almeida, A.M., Near-surface circulation and kinetic energy in the tropical Indian Ocean derived from Lagrangian drifters, *J. Mar. Res*., 57(1999) 885–907, doi:10.1357/002224099321514088.

4 Shetye, S.R., Gouveia, A.D., Shenoi, S.S.C., Sundar, D., Michael, G.S., Almeida, A.M. & Santanam, K., Hydrography and circulation off the west coast of India during the Southwest Monsoon 1987, *J. Mar. Res*., 48(1990) 359–378.

5 Shetye, S.R., Gouveia, A.D., Shenoi, S.S.C., Michael, G.S., Sundar, D., Almeida, A.M. & Santanam, K., The coastal current off western India during the northeast monsoon, *Deep Sea Res.*, 38(1991) 1517–1529.

6 Shetye, S.R., Gouveia, A.D., Shenoi, S.S.C., Sundar, D., Michael, G.S. & Nampoothiri, G., The western boundary current of the seasonal subtropical gyre in the Bay of Bengal, *J. Geophys. Res*., 98(1993) 945–954, doi: 10.1029/92JC02070.

7 Shetye, S.R., Shenoi, S.S.C., Gouveia, A.D., Michael, G.S., Sundar, D. & Nampoothiri, G., Wind-driven coastal upwelling along the western boundary of Bay of Bengal during southwest monsoon, *Cont. Shelf Res*., 11(1991) 1397–1408, doi:10.1016/0278-4343(91)90042-5.

8 Shetye, S.R., Gouveia, A.D., Shankar, D., Shenoi, S.S.C., Vinayachandran, P.N., Sundar, D., Michael, G.S. & Nampoothiri, G., Hydrography and circulation in the western Bay of Bengal during the northeast monsoon, *J. Geophys. Res*., 101(1996) 14011–14025, doi: 10.1029/95JC03307.

9 Bruce, J.G., Comparison of near surface dynamic topography during the two monsoons in the western Indian Ocean, *Deep-Sea Research*, 15 (1968) 665–667.

10 Bruce, J.G., Johnson, D.R. & Kindle, J.C., Evidence for eddy formation in the eastern Arabian Sea during the northeast monsoon, *J. Geophys. Res*., 99 (1994) 7651–7664.

11 Shenoi, S.S.C., Shankar, D. & Shetye, S.R., Remote forcing annihilates barrier layer in southeastern Arabian Sea, *Geophys. Res. Lett*., 31(2004) L05307, doi: 10.1029/2003GL019270.

12 Shankar, D. & Shetye, S.R., On the dynamics of the Lakshadweep High and Low in the southeastern Arabian Sea, *J. Geophys. Res*., 102(1997) 12551–12562.

13 Mc Creary, J.P., Kundu, P.K. & Molinari, R.L., A numerical investigation of the dynamics, thermodynamics and mixed-layer processes in the Indian Ocean, *Prog. Oceanogr.*, 31(1993) 181–244, doi:10.1016/0079-6611(93)90002-U.

14 Yu, L., O'Brien, J.J. & Yang, J., On the remote forcing of the circulation in the Bay of Bengal, *J. Geophys. Res*., 96(1991) 20449–20454, doi: 10.1029/91JC02424.

15 Potemra, J.T., Luther, M.E. & O'Brien, J.J., The seasonal circulation of the upper ocean in the Bay of Bengal, *J. Geophys. Res*., 96(1991) 12667–12683.

16 Shankar, D., Mc Creary, J.P., Han, W. & Shetye, S.R., Dynamics of the East India Coastal Current 1. Analytic solutions forced by interior Ekman pumping and local alongshore winds, *J. Geophys. Res*., 101(1996) 13975–13991, doi: 10.1029/96JC00559.

17 Mc Creary, J.P., Han, W., Shankar, D. & Shetye, S.R., Dynamics of the East India Coastal Current 2. Numerical solutions, *J. Geophys. Res*., 101(1996) 13993–14010, doi: 10.1029/96JC00560.

18 Shenoi, S.S.C., Shankar, D. & Shetye, S.R., On the sea surface temperature high in the Lakshadweep Sea before the onset of the southwest monsoon, *J. Geophys. Res.*, 104(1999) 15703– 15712, doi: 10.1029/1998JC900080.

19 Shenoi, S.S.C., Shankar, D., Michael, G.S., Kurian, J., Varma, K.K., Rameshkumar, M.R., Almeida, A.M., Unnikrishnan, A.S., Fernandes, W., Barreto, N., Gnanaseelan, C., Mathew, R., Praju, K.V. & Mahale, V., Hydrography and water masses in the southeastern Arabian Sea during March-June 2003, *J. Earth Syst. Sci.,* 144(2005) 475-491.

20 Shankar, D., Vinayachandran P.N. & Unnikrishnan, A.S., The monsoon currents in the north Indian Ocean, *Prog. Oceanogr.,* 52(2002) 63–120.

21 Goswami B N, South Asian monsoon, in *intraseasonal variability in the atmosphere-ocean climate system*, edited by W. K. M. Lau and D. E. Waliser, (Springer, Berlin) 2005, pp. 19–55.

22 Zhang, C., Madden-Julian Oscillation, *Rev. Geophys*., 43(2005) RG2003, doi: 10.1029/2004RG000158.

23 Wheeler, M.C. & Hendon, H.H., An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction, *Mon. Weather Rev*., 132(2004) 1917–1932, doi: 10.1175/1520-0493(2004)132<1917: AARMMI>2.0.CO.

24 Sanilkumar, K.V., Kuruvilla, T.V., Jogendranath, D. & Rao, R.R., Observations of the Western Boundary Current of the Bay of Bengal from a hydrographic survey during March 1993, *Deep Sea Res., Part I,* 44(1997) 135–145, doi: 10.1016/S09670637(96)00036-2.

25 Babu, M.T., Sarma, Y.V.B., Murty, V.S.N. & Vethamony, P., On the circulation in the Bay of Bengal during Northern spring inter-monsoon (March-April, 1987), *Deep Sea Res., Part II*, 5(2003) 855–865, doi: 10.1016/S0967-0645(02)00609-4.

26 Mariano A J, Ryan E H, Perkins B D, & Smithers S, *The Mariano Global Surface Velocity Analysis 1.0*, (Rep. CG-D-34 – 95, U.S. Coast Guard, Washington D. C.) 1995, pp. 55.

27 Vinayachandran, P.N., Kagimoto, T., Masumoto, Y., Chauhan, P., Nayak, S.R. & Yamagata, T., Bifurcation of the East India Coastal Current east of Sri Lanka, *Geophys. Res. Lett.*, 32(2005) L15606, doi: 10.1029/2005GL022864.

28 Durand, F., Shankar, D., Birol, F. & Shenoi, S.S.C., Spatiotemporal structure of the East India Coastal Current from satellite altimetry, *J. Geophys. Res*., 114(2009) C02013, doi: 10.1029/2008JC004807.

29 Han, W. & Webster, P., Forcing mechanisms of sea level inter-annual variability in the Bay of Bengal, *J. Phys. Oceanogr*., 32(2002) 216–239, doi: 10.1175/1520-0485(2002)032.

30 Durand, F., Shankar, D., Birol, F. & Shenoi, S.S.C., Estimating boundary currents from satellite altimetry: A case study for the east coast of India, *J. Oceanogr*., 64(2008) 831–845, doi: 10.1007/s10872-008-0069-2.

31 Vignudelli, S., Cipollini, P., Astraldi, M., Gasparini, G.P. & Manzella, G.M.R., Integrated use of altimeter and in situ data for understanding the water exchanges between the Tyrrhenian and Ligurian seas, *J. Geophys. Res*., 105(2000) 19649–19663, doi: 10.1029/2000JC900083.

32 Birol F, Roblou L, Lyard F, Llovel W, Durand F, Renault L, Dewitte B, Morrow R & Menard Y, *Towards using satellite altimetry for the observation of coastal dynamics*, Paper presented at *15 Years of Progress in Radar Altimetry Symposium, Eur. Space Agency, Venice,* Italy, 2006.

33 Shenoi, S.S.C., Antony, M.K. & Sundar, D., Nature of the observed oscillatory flows in the shelf waters of the western continental shelf of India, *J. Coast. Res.,* 4(1988) 617-626.

34 Shenoi, S.S.C. & Antony, M.K., Current measurements over the western continental shelf of India, *Cont. Shelf Res*., 11(1991) 81–93.

35 Vialard, J., Shenoi, S.S.C., Mc Creary, J.P., Shankar, D., Durand, F., Fernando, V. & Shetye, S.R., Intraseasonal response of the northern Indian Ocean coastal waveguide to the Madden-Julian Oscillation, *Geophys. Res. Lett.,* 36(2009) L14606, doi: 10.1029/2009GL038450.