

Low frequency variability of the Indian Ocean from TOPEX/POSEIDON sea surface height anomalies

Y.K. Somayajulu, V.S.N. Murty and Y.V.B. Sarma
National Institute of Oceanography, Dona Paula, Goa-403 004, India
E-mail: yksoma@csnio.ren.nic.in

Abstract

The sea surface height (SSH) anomalies derived from TOPEX/POSEIDON altimeter have been utilized to study the variability of surface circulation in the Indian Ocean during 1993-1999. The Western Bay, south-eastern Arabian Sea, regions off Somalia and off Sumatra present large variability on both seasonal and inter-annual time scales. The SSH anomalies off Sumatra show dominant influence of warm (cold) ENSO events with peak negative (positive) anomalies coinciding with El Nino (La Nina). These anomalies extend northward along the rim of the eastern, northern and up to the western Bay of Bengal, effecting the surface circulation on the seasonal and inter-annual time scales. The Bay of Bengal responds to all the phases of warm and cold ENSO events and the surface circulation is thus characterized by meso-scale weak/intense eddies. The forcing of the warm and cold ENSO events on the Bay circulation is evident from the absence of both North Equatorial Current in the southern Bay and intrusion of Southwest Monsoon Current into the Bay during winter and summer seasons of 1998. On the contrary, the Arabian Sea responds only to the intense warm (cold) ENSO event during winter (summer) monsoon. However, the surface circulation in this basin does not vary much during summer (winter) monsoon due to warm (cold) ENSO event in the year 1997 (1999).

1. Introduction

The surface circulation of the Indian Ocean undergoes large seasonal variation due to seasonally reversing monsoon forcing - southwest monsoon (June-September) and northeast monsoon (December-February). The seasonal variability is more predominant in the northern regions. In addition to the strong northward flowing Somali Current and the upwelling off the coast of Somalia, the southwest monsoon also drives open ocean Ekman pumping in the Arabian sea. In the Bay of Bengal, the fresh water inputs through river run off generate wide variations in surface salinity which results in complex mesoscale surface circulation. Several studies emphasized the role of the Kelvin and Rossby waves on Indian Ocean circulation. Yu *et al.* (1991) and Potemra *et al.* (1991) showed that the equatorial Kelvin waves significantly influence the seasonal circulation in the Bay of Bengal through reflected Rossby waves. The southern tropical Indian Ocean is connected to the Pacific Ocean through the Indonesian throughflow. Recent studies point out that the interannual variation in the sea level off the Indonesian Islands is connected to the propagating waves in the equatorial Indian Ocean. The seasonal cycle of surface circulation is well documented. To understand the interannual variation in the mesoscale circulation, satellite observations of ocean surface features (particularly SSH data from T/P altimeter) are ideal because of their basin-wide data coverage at short time intervals. In this paper, we examine the annual varia-

tion of SSH anomaly in the Indian Ocean from 1993 to 1999 and discuss the inter-annual variability in the meso-scale circulation features in relation to El Nino Southern Oscillation (ENSO) events.

2. Data analysis

The processed T/P altimeter derived SSH anomalies for the six year period, 1993-1999 supplied by AVISO (Archiving, validating and interpretation of satellite oceanographic data), CNES, France are used for the area of the Indian Ocean between 30°N - 40°S, 30°-120°E in the present analysis. This data set is already

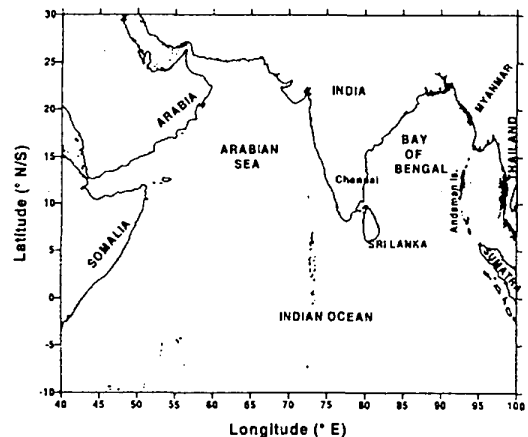


Fig. 1. Area map.

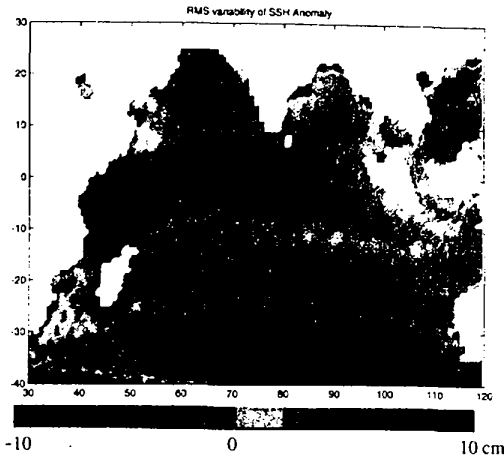


Fig. 2. RMS variability of SSH anomaly for T/P cycles 11 to 268 during January 1993–December 1999.

corrected for all environmental and orbit errors. The along-track anomalies are gridded on to a regular 0.5° by 0.5° grid by means of Gaussian interpolation following the procedure of Cipollini *et al.* (1997) with a full width half maximum of 150 km and a search radius of 200 km. The Indian Ocean is divided into four regions; Arabian Sea, Bay of Bengal, equatorial belt and southern tropical Indian Ocean (Fig. 1). In order to analyze the spatial variability (year-to-year) and also the temporal variability of SSH anomaly, the equatorial belt and the southern tropical Indian Ocean are further divided in to western and eastern sectors.

3. Results and Discussion

Large variability of SSH anomaly ($rms > 10$ cm) is noticed along the west coast of Sumatra, Thailand, Myanmar and along the western periphery of the Bay of Bengal (Fig. 2). It is interesting to note that the regions of fresh water influx, i.e. the head of the Bay and northern Andaman Sea show maximum ($rms \approx 14$ cm) variability. The central Bay, northern Arabian Sea and the equatorial region show conspicuously low rms variability. The band of low SSHA around the equator, gradually tapers towards the east coast of Africa. In the southern Indian Ocean, the SSHA is maximum in the Agulhas retroflection region (> 14 cm) and along the Mozambique coast (10–14 cm). The south equatorial current (SEC) which forms the northern boundary of the subtropical gyre is characterized by a broad band of relatively higher rms variation (8–10 cm) embedded with multiple peaks presumably propagating westwards.

3.1 Annual mean surface circulation

All the annual maps of SSHA (Fig. 3a-g) invariably show that the western parts of both Bay of Bengal and

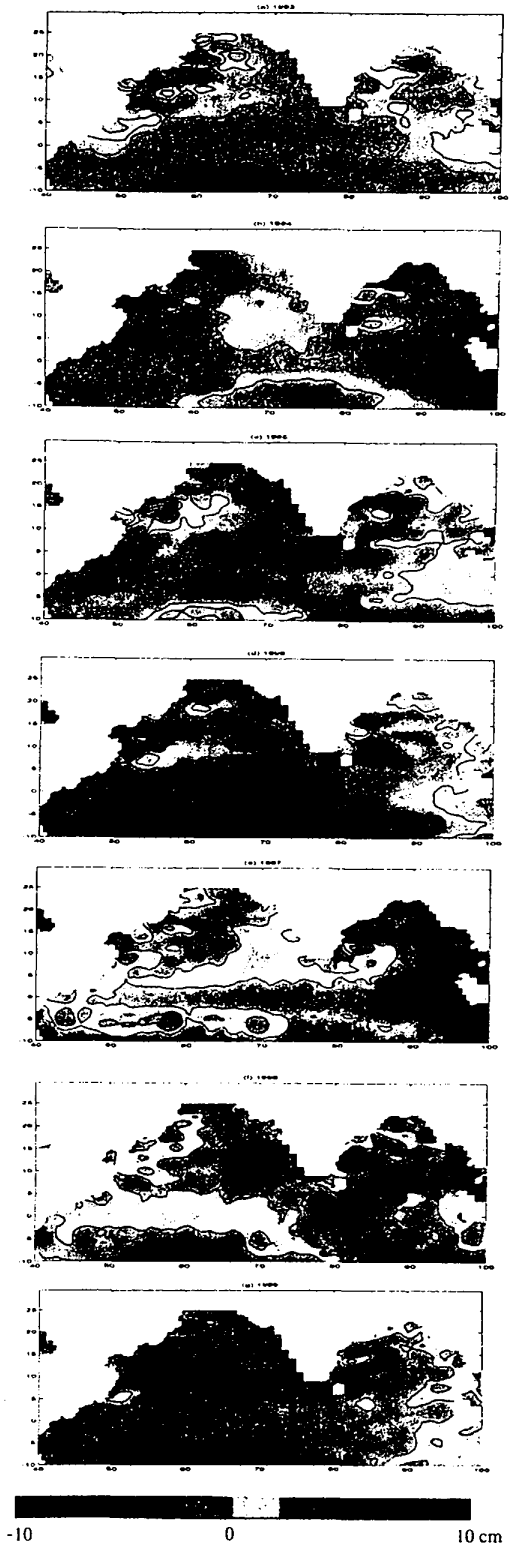


Fig. 3. Annual mean (1993-1999) SSH anomaly in the Indian Ocean.

the Arabian Sea are characterized by numerous meso-scale cells of positive and negative SSHA. Positive cells of SSHA describe anti-cyclonic (clockwise) circulation features while the negative cells that of cyclonic (anti-clockwise) circulation in the Northern Hemisphere and vice versa in the Southern Hemisphere. The magnitude and the location of the cells vary from year to year. It is seen that the positive anomaly cells observed in a certain year are replaced by the negative anomaly cells or vice versa. This may be the result of the large scale changes in the surface circulation. During the years 1993, 1996 and 1999 (Figs. 3a, 3d and 3g), the SSHA patterns are similar with a large negative anomaly (-8 to -12 cm) occurring between 5° – 10° S and 60° – 70° E. On the contrary, during the years 1994, 1995, 1997 and 1998, a large positive anomaly prevails between 5° – 10° S and 60° – 80° E (Figs. 3b, 3c, 3e and 3f). However, there appears a westward shift in the positive anomaly from 1994 to 1998 with a weaker anomaly in 1995 and 1997. This variability appears to be associated with the dynamics of ENSO phenomenon which is characterized by a moderate warm ENSO event in 1994 to intense warm event in 1998. During the years of ENSO events, large negative SSH anomaly occurred off Sumatra coast (Fig. 3b and 3e). Murtugudde *et al.*, (1999), Potemra and Lukas (1999) identified this negative anomaly in SSH with large negative SST anomaly caused by the anomalous southwesterly winds blowing parallel to the Sumatra coast. These winds forced the coastal upwelling and consequent reduction in SST anomaly. The large positive SSH anomaly around 10° S in 1998 has been associated with warmer sea surface temperatures under weak southwest trade winds and low latent heat flux exchange across the air-sea interface (Murtugudde, 1998 and Webster, 1999). The negative SSH anomaly observed off Sumatra coast extended northwards along the coasts of Thailand and Myanmar in the Andaman Sea and continued into the northern and western Bay of Bengal. However, along the east coast of India, the large negative band of SSHA is interrupted by alternating positive and negative cells (> 12 cm and < -12 cm). The locations of these positive and negative cells swap during ENSO and non-ENSO years. In the Arabian Sea also the annual mean surface circulation exhibited wide variability, particularly off Somali coast, in association with the ENSO events. The above also suggests that there exists inter-annual variation in the surface circulation, as seen from SSH anomaly variations, under the influence of ENSO events.

Recent studies in the eastern equatorial Indian Ocean (EEIO) through direct current measurements, GCM simulations and hydrography documented variability in the upper layer circulation which has a direct link to

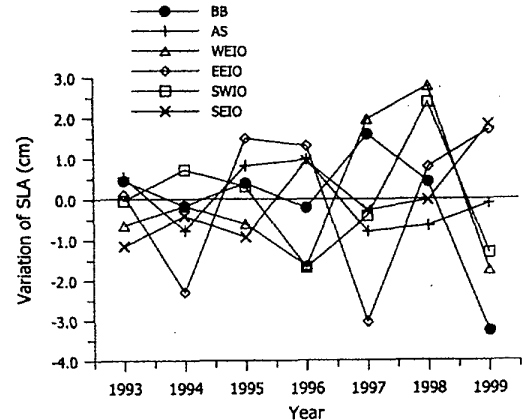


Fig. 4. Inter-annual variability of SSH anomaly at selected regions.

the SSHA variations off Sumatra coast during warm ENSO event of 1994 (Reppin *et al.*, 1999, Vinayachandran *et al.*, 1999 and Unnikrishnan *et al.*, 2000).

3.2 Inter-annual variability in selected regions

We have considered six regions: Bay of Bengal, BB (north of 5° N); Arabian Sea, AS (north of 5° N), Western Equatorial Indian Ocean, WEIO (5° S– 5° N, 45° – 55° E); Eastern Equatorial Indian Ocean, EEIO (5° S– 5° N, 90° – 100° E); Southwest Indian Ocean, SWIO (5° S– 20° S, 50° – 60° E) and Southeast Indian Ocean, SEIO (5° S– 20° N, 90° – 100° E) to quantify the magnitude of the inter-annual variability in each region from 1993 to 1999. For this purpose, the deviation of SSH anomaly over the 7 year mean SSHA is obtained and presented in Fig. 4.

Among the above regions, the EEIO showed larger amplitude of inter-annual variation with large negative values (-4 to -6 cm) corresponding to warm ENSO years of 1994 and 1997 and peak positive values ($+3$ cm) during cold ENSO years of 1995 and 1996. This highlights the response of the EEIO with a negative correlation to the ENSO events. Interestingly, the basin scale response of the Bay of Bengal to the ENSO events is also negatively correlated but with lesser magnitudes (± 1 cm), however, in phase with the sea level variation off Sumatra coast. More interestingly, the basin scale response of the Arabian Sea is significant only during the intense warm ENSO event of 1997 ($+1.5$ cm) and cold ENSO event of 1999 (-2.5 cm). This inter-annual variation is in-phase with the ENSO events while it is negatively correlated to the sea level variation off Sumatra coast. The inter-annual variation of SSHA in the WEIO region is similar to that of the Arabian Sea with relatively higher amplitudes (-2.0 to $+3.0$ cm) indicating the response of WEIO to

both ENSO events and sea level variation off Sumatra coast. This asymmetry in the deviation of SSH anomaly (over the 7 year mean) between the eastern and western basins suggest the existence of the internal mode (Dipole) of the Indian Ocean (Saji *et al.*, 1999). This analysis also points out that the Indian Ocean Dipole is related to all the ENSO events, rather than independent of them as Saji *et al.* noted. However, the strength of the Dipole appears to be weak during weak warm/cold ENSO events.

The inter-annual variation (deviation of the anomaly over the 7 year mean) of the SSH anomaly in the SEIO region is out-of-phase to that in the SWIO region. The response of the SWIO region to the variability in the ENSO events is rather considerable during 1996-1999. This is evident from the increase of the anomaly from -4 cm in 1996 (cold ENSO event) to above +6 cm in 1998 (intense warm ENSO) followed by abrupt decrease (-4 cm) in 1999 (cold ENSO event). The deviation of SSH anomaly in the SEIO shows a mixed response to the ENSO events. We attribute this mixed response to the varying transports of Indonesian Throughflow from the western Pacific as well as the transport of South Equatorial Current during the ENSO events.

The above observed inter-basin response to the intense warm/cold ENSO events on the annual time scale is further looked into seasonal time scale to identify the amplitude of variability in the sea level in a given season. For this purpose we have examined the maps of SSHA for the period July (Summer) 1997 to April (Spring) 1999 spanning over the intense El Nino and La Nina events. Fig. 5 shows the seasonal variation of SSH anomaly for the representative months of each season - July (boreal summer/southwest monsoon) and October (post-monsoon/boreal Fall), January (boreal winter/northeast monsoon) and April (pre-monsoon/boreal Spring).

3.3 Response of seasonal surface circulation to warm and cold ENSO events

The temporal variation of Southern Oscillation Index (SOI) and the associated temperature deviation in the year 1997 indicates that the warming phase of ENSO began from the boreal Spring, attained peak value by boreal Summer season and persisted through boreal Fall. During this period (July–October), SSH anomaly off Sumatra coast is persistently negative and its influence is seen along the eastern periphery of the Bay (Figs. 5a and 5b). During July, the large negative anomaly cell in the western Bay of Bengal is embedded between two positive anomaly cells of relatively smaller size. As the El Nino intensified, the sea level off Sumatra deepened (more negative) while the meso-scale circulation in the western Bay weakened. The

studies of Reppin *et al.*, (1999) and Vinayachandran *et al.* (1999) have shown that the eastward transport of the Fall equatorial Wyrтки Jet reduced significantly (compared to that of Spring Jet) during the moderate ENSO year of 1994. During this ENSO period, Unnikrishnan *et al.* (2000) noticed an anomalous westward flow in the eastern equatorial Indian Ocean that effected the eastward transport of Fall Wyrтки Jet. As the circulation along the east coast of India is effected by the equatorial Kelvin waves (Mc Creary *et al.*, 1996), it is speculated that the changes in the transport of Wyrтки Jet and propagating waves in the EEIO would modify the mesoscale circulation in the western Bay. This is evident from the SSH anomaly map of October 1997 (Fig. 5b).

The influence of warm ENSO event gradually faded off Sumatra coast by Spring 1998 when the meridional bands of alternating positive and negative SSH anomaly occupied the EEIO, the Andaman Sea and the Bay of Bengal (Figs. 5c and 5d). By July 1998, a band of positive anomaly extended from the SEIO region to Sumatra coast indicating the beginning of the influence of cold ENSO event and thus the meso-scale circulation cells disappeared in the western Bay (Fig. 5e) as in the case of October 1997 (Fig. 5b). As the cold ENSO intensified, the positive anomaly also intensified and widened off Sumatra coast and brought out changes in the western Bay with meso-scale circulation cells reappearing by January 1999 (Fig. 5g). By Spring 1999, the positive SSH anomaly from Sumatra coast extended into the Andaman Sea while the meso-scale eddies persisted in the western Bay between 12° and 16°N (Fig. 5h).

During the warm ENSO event (July 1997), a broad westward flow is noticed between Sumatra coast and 80°E in the vicinity of the equator. This westward flow encountered the eastward flowing southwest monsoon current (SWMC) and forced its entry into the southwestern Bay from south of Sri Lanka (band of positive SSHA in Fig. 5a). A meso-scale anticyclonic eddy off Sri Lanka separates the SWMC from the westward flow. Similar surface circulation features are reported during July-August 1994, the warm ENSO year (Unnikrishnan *et al.*, 2000). However, during the period of cold ENSO event (July 1998), the SWMC is limited only to the region west of 75°E. This conspicuous absence of monsoon current into the Bay affected the circulation in the central and western Bay, in contrast to the meso-scale cells in July 1997.

The surface circulation of the Arabian Sea during July 1997 shows the known features of circulation - the Great Whirl off Somalia, large anticyclonic gyre in the central Arabian Sea, the southward surface flow along the west coast of India and upwelling along the Arabian

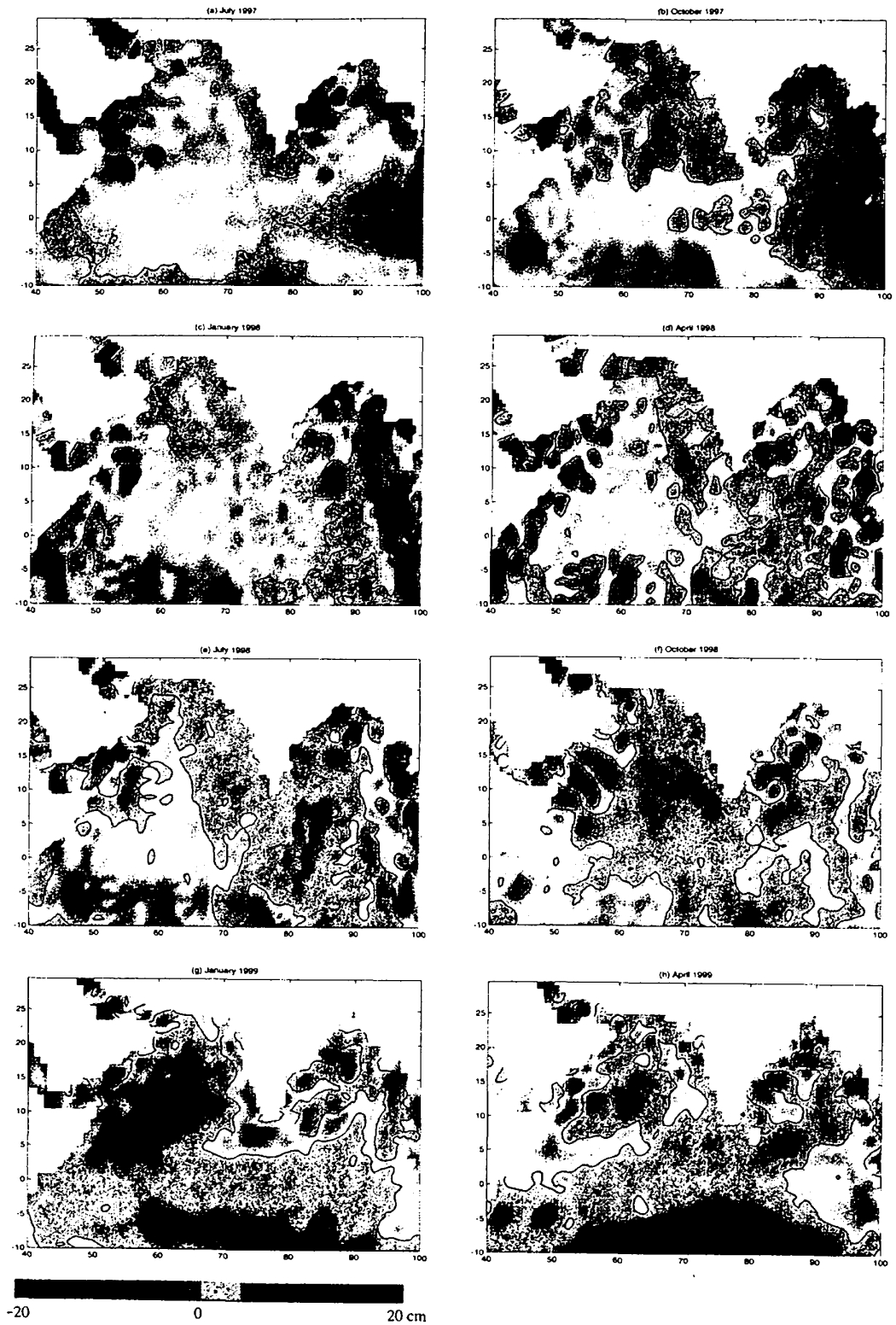


Fig. 5. Seasonal variability maps of SSH anomaly during (a-d) El Niño and (e-h) La Niña years.

coast (Fig. 5a). These features are nearly absent during July 1998 (Fig. 5e), the period of cold ENSO event. Similarly, the surface circulation features during the winter monsoon of January 1998 (Fig. 5c) and January 1999 (Fig. 5g) show considerable differences. The SSH anomaly field in January 1999 (the period of cold ENSO event) follows the well documented circulation features with a large cyclonic gyre in the central part and a poleward surface flow along the west coast of India with an embedded Lakshadweep High (Fig. 5g). These features are totally absent during January 1998, the period of decaying phase of the warm ENSO.

Thus, the present study highlights that the Bay of Bengal responds to all the phases of warm and cold ENSO events and the surface circulation is characterized by weak to intense meso-scale cells/eddies. The forced restriction to the westward flowing North Equatorial Current (NEC) in the southern Bay and to the eastward flowing SWMC into the Bay during the years of warm (Jan., 1998) and cold (Jul., 1998) ENSO events affected the seasonal circulation in the Bay. Besides, the variability in the propagating Kelvin waves and Rossby waves during the ENSO events compounds to the above variability in the meso-scale circulation. On the contrary, the seasonal surface circulation in the Arabian Sea did not change much during the summer monsoon due to warm ENSO event (Jul., 1997) and during the winter monsoon due to cold ENSO event (Jan., 1999). However, this basin responds to the intense warm ENSO events during winter monsoon and to the cold ENSO events during the summer monsoon.

Acknowledgements

The authors are grateful to Director, NIO for his keen interest in this study. They wish to acknowledge the support of AVISO, France for providing the CORSSH and SLA data on CD-ROMs. This is NIO contribution No. 3592.

References

- AVISO User Handbook "Sea Level Anomalies (SLAs)" AVI-NT-011-312-CN, Edition 3.0, Nov. 1997, 23 pp.
- Cipollini, P., D. Cromwell, M.S. Jones, G.D. Quartly and P.G. Challenor (1997) Concurrent altimeter and infrared observations of Rossby wave propagation near 34°N in the northeast Atlantic, *Geophys. Res. Lett.*, 24, 889-892.
- Potemra, J.T., M.E. Luther, and J.J. O'Brien, The seasonal circulation of the upper ocean in the Bay of Bengal, *J. Geophys. Res.*, 96, 12,667-12,683, 1991.
- Potemra, J.T., and R. Lukas (1999) Seasonal to interannual modes of sea level variability in the western Pacific and eastern Indian Oceans, *Geophys. Res. Lett.*, 26, 365-368.
- McPhaden, M.J. (1999) Genesis and evolution of the 1997-98 El Nino, *Science*, 283, 950-954.
- Murtugudde, R.G., A.J. Busalacchi and J. Buauchamp (1998) Seasonal-to-interannual effects of the Indonesian throughflow on the tropical Indo-Pacific basin, *J. Geophys. Res.*, 103, 21425-21441.
- Murtugudde, R.G., S.R. Signorini, J.R. Christian, A.J. Busalacchi, C.R. McClaine and J. Picaut (1999) Ocean color variability of the tropical Indo-Pacific basin observed by SeaWiFS during 1997-1998, *J. Geophys. Res.*, 104, 18351-18366.
- Reppin, J., F.A. Schott, J. Fischer and D. Quadfasel (1999) Equatorial currents and transports in the upper central Indian Ocean: Annual cycle and interannual variability, *J. Geophys. Res.*, 104, 15495-15514.
- Saji, N.N., B.N. Goswami, P.N. Vinayachandran and Y. Yamagata (1999) A dipole mode in the tropical Indian ocean, *Nature*, 401, 360-363.
- Vinayachandran, P.N., N.H. Saji and T. Yamagata (1999) Response of the equatorial Indian Ocean to an unusual wind event during 1994, *Geophys. Res. Lett.*, 26, 1613-1616.
- Unnikrishnan, A.S., V.S.N. Murty, M.T. Babu, C.K. Gopinathan and R.J.K. Charyulu (2000) On the anomalous current structure in the eastern equatorial Indian ocean during southwest monsoon of 1994, *J. Mar. Freshwat Res.* (Commun.)
- Webster, P.J., A.M. Moore, J.P. Loschnigg and R.R. Leben (1999) Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98, *Nature*, 401, 356-360.
- Yu, L., J.J. Obrien and Y. Yang (1991) On the remote forcing of the circulation in the Bay of Bengal, *J. Geophys. Res.*, 96, 20449-20454.