Bifurcation of the East India Coastal Current east of Sri Lanka

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[1] The East India Coastal Current (EICC) flows equatorward during October–December carrying low salinity water from the Bay of Bengal en route. Using results from a high resolution ocean general circulation model, satellite altimeter data, Argo float profiles and ocean color images we show that the EICC bifurcates east of Sri Lanka. One part continues along the coast of Sri Lanka but the major part of the EICC, called here as the East Sri Lanka Jet (ESLJ) flows eastward into the Bay of Bengal. As a result of this bifurcation, there is offshore transport of chlorophyll *a* rich low salinity water from the coast of Sri Lanka. Altimeter data from 1993–2004 show that the bifurcation occurred every year except during the Indian Ocean Dipole (IOD) years of 1994 and 1997. The bifurcation occurs when an anticyclonic eddy that propagates westward ahead of a downwelling Rossby wave front impinges on the Sri Lanka coast. This new finding suggests that the main route of the low salinity water from the Bay of Bengal into the southeastern Arabian Sea may not be along the coast around Sri Lanka but through the Winter Monsoon Current. **Citation:** Vinayachandran, P. N., T. Kagimoto, Y. Masumoto, P. Chauhan, S. R. Nayak, and T. Yamagata (2005), Bifurcation of the East India Coastal Current east of Sri Lanka, *Geophys. Res. Lett.*, *32*, L15606, doi:10.1029/2005GL022864.

1. Introduction

[2] The circulation along the western boundary of the Bay of Bengal consists of the East India Coastal Current (EICC) that reverses its direction with seasons. During the premonsoon months of February–April, the EICC flows poleward [*Legeckis*, 1987] as the western arm of a subtropical gyre [*Shetye et al.*, 1993]. During summer monsoon, the EICC flows poleward along the southern part of the Indian coast and equatorward along the northern part [*Shetye et al.*, 1991] whereas, during October–December, the EICC flows equatorward along the entire Indian coast [*Shetye et al.*, 1996] carrying low salinity water from the Bay of Bengal en route. Within this seasonal cycle, the southward flowing EICC during October–December has a crucial role in the fresh water balance of the north Indian Ocean because it is an efficient conduit for the export of low salinity water from the Bay of Bengal [*Jensen*, 2001]. This low salinity water eventually finds its way into the southeastern Arabian Sea and plays an important role on the formation of a mini warm pool during the premonsoon months [*Rao and Sivakumar*, 1999; *Shenoi et al.*, 1999].

[3] There are two routes for the low salinity water from the Bay of Bengal into the southeastern Arabian Sea. One is along the coast, around Sri Lanka and the southern tip of India during October–November and the other is through the Winter Monsoon Current during December–March which is fed by the EICC [*Shankar et al.*, 2002]. The low salinity water observed in the southeastern Arabian Sea during November–December [*Boyer et al.*, 2002] and numerical models which show that the EICC flows around India and Sri Lanka into the Arabian Sea [*Han and McCreary*, 2001; *Vinayachandran and Yamagata*, 1998] suggest that the EICC is a definite conduit.

[4] However, there are no observations around Sri Lanka and the tip of India that show the complete route of the low salinity water along the coast into the southeastern Arabian Sea. In this paper, we show using results from a high resolution ocean general circulation model (OGCM), high resolution maps of ocean color, satellite altimeter data and salinity profiles from an Argo float that the EICC bifurcates east of Sri Lanka. The model results are presented in the next section and observational evidences for the bifurcation are presented in Section 3. The mechanisms that lead to the bifurcation are presented in Section 4 and we summarize the results in the Section 5.

2. Model Simulation

[5] The OGCM used here is known as OFES (OGCM for Earth Simulator [*Masumoto et al.*, 2004]) and it is based on the Modular Ocean Model (MOM3) developed at GFDL. The model domain is global and has high horizontal and vertical resolutions with a grid spacing of 1/10° in both longitude and latitude. There are 54 levels in the vertical with 13 levels in the upper 100m. The vertical mixing is based on the KPP boundary layer mixing parameterization [*Large et al.*, 1994] and horizontal mixing uses a bi-harmonic operator which selects viscosity and diffusivity coefficients that are varying in space. The model is forced for 50 years using climatological winds, heat and freshwater fluxes from NCEP/NCAR reanalysis [*Kalnay et al.*, 1996]. The model salinity, in addition, is restored to climatological monthly mean values with a time scale of 6 days. Results from the 50th year of the model run for the Bay of Bengal is used for the present study.

[6] The EICC commences to flow equatorward all along the east coast of India after the withdrawal of the southwest monsoon. Ship-drifts and satellite altimetry [*Shankar et al.*,

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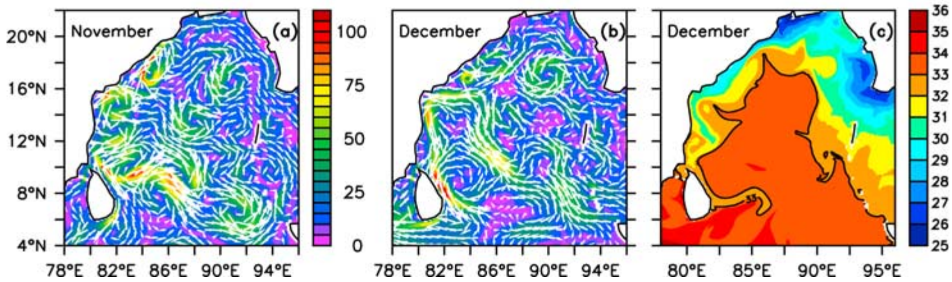

Figure 1. Monthly mean currents from the model at the first model level (2.5m) for (a) November and (b) December. Model current speeds (in cm s^{-1}, shaded) and vectors (arrows) smoothed by a 3-point Hanning smoother in space are shown at every sixth grid point. (c) The salinity (psu) field simulated by the model for 15 December. The contour indicates 33 psu isohaline.

2002] show the EICC along the entire east coast of India during October–December. Monthly mean surface currents from the model (Figure 1) show an equatorward EICC all along the Indian coast during the same period. The most striking feature of the model currents is that the EICC during November consist of three eddies (Figure 1a). Hydrographic observations during December 1991 [*Shetye et al.*, 1996] also showed presence of eddies. The model currents during December (Figure 1b) show a well organized equatorward flow to the south of 16°N. The EICC is fed by two branches of shoreward flow, one around 16°N and the other between 10°N–12°N. Similar shoreward flows were also noticed in the hydrographic survey during 1991 [*Shetye et al.*, 1996].

[7] During November, after flowing eastward till about the middle of Sri Lankan coast, the model EICC bifurcates and its major part turns offshore, meanders towards southeast and then turns in an anticlockwise direction (Figure 1a). For convenience we call the current that flows offshore east of Sri Lanka as East Sri Lanka Jet (ESLJ). The rest of the EICC flows as a narrow weak current along the Sri Lankan coast. The transport of the EICC east of Sri Lanka reduced from 2.5Sv to 0.4Sv after its bifurcation. The location of bifurcation shifts to the southeastern tip of Sri Lanka during December (Figure 1b). In addition, the ESLJ has a reduced offshore extent than in November. In brief, the model simulations clearly show that the EICC bifurcates east of Sri Lanka. The major part flows eastward into the Bay of Bengal as ESLJ carrying low salinity water along its path (Figure 1c) and only a small part continues along the coast of Sri Lanka.

3. Observational Evidences

3.1. Altimetry

[8] We have used the merged TOPEX/Poseidon - ERS data set [*Ducet et al.*, 2000] obtained from AVISO. Sea surface height anomalies (SSHA) from this data set available at a horizontal resolution of 1/3° × 1/3° at 7 day intervals are used for calculation of geostrophic currents.

[9] Geostrophic currents superposed on SSHA for two selected years (Figure 2) show the equatorward EICC south of about 18°N, very similar to the OFES simulation. The geostrophic flow field clearly show that the EICC bifurcates east of Sri Lanka (Figures 2c, 2e, and 2f). The major part of the current flows eastward after the occurrence of the bifurcation and the rest continues westward around the coast of Sri Lanka. As in the model simulation (Figure 1), the circulation in the southwestern Bay of Bengal consists of a cyclonic gyre [*Eigenheer and Quadfasel*, 2000; *Vinayachandran and Yamagata*, 1998; *McCreary et al.*, 1993] that flows anti-clockwise around a low in SSHA and the bifurcation occurs along the southern edge of this gyre.

3.2. Argo Float Profiles

[10] Salinity profiles from an Argo (http://www.ifremer.fr/coriolis/cdc/argo.htm) float also provide evidences for the bifurcation of the EICC east of Sri Lanka. The Argo float

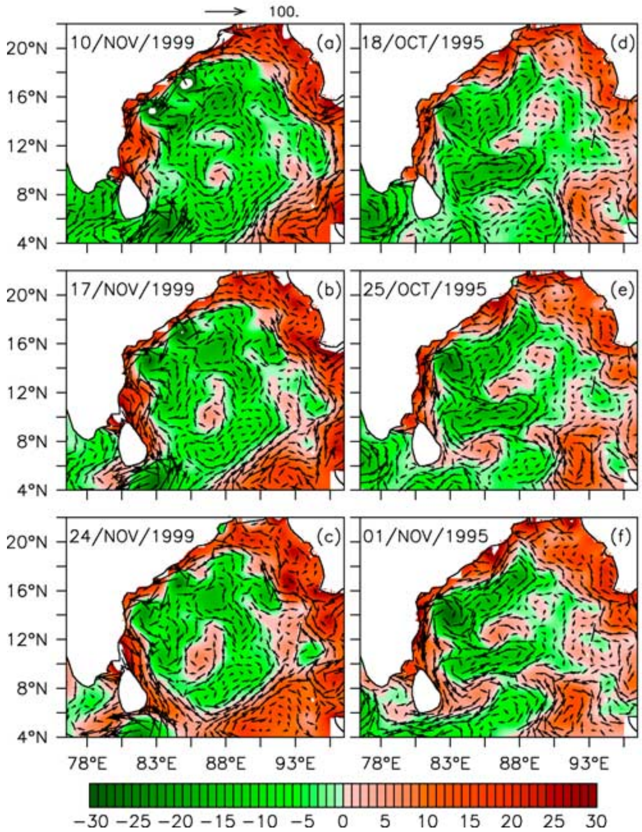

Figure 2. Sea surface height anomalies (shaded, in cm) and geostrophic currents (vectors, in cm s^{-1}) for (left) 1999 and (right) 1995.

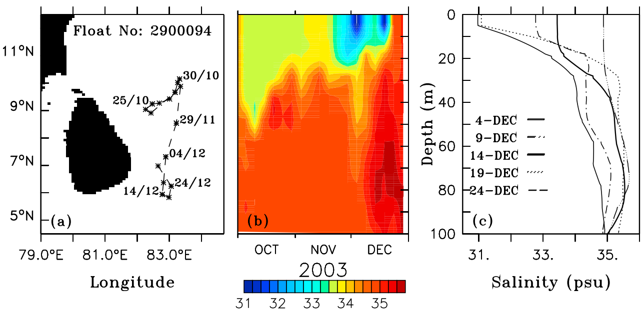

Figure 3. (a) Track of the Argo float with WMO identification No. 2900094 during October–December 2003. (b) Time-depth section of salinity (psu, shaded) along the track shown in Figure 3a. (b) vertical profiles of salinity for selected days in December 2003.

with WMO identification No. 2900094 deployed at 82.65°E; 6.98°N measured temperature and salinity profiles in the southwestern Bay of Bengal from August 21, 2002 to December 29, 2003 (Figure 3a). The data from this float, sampled at approximately 5m, 10m and for every 10m in the top 120m, is available every 5 days. The float profiled southeast of Sri Lanka during December 2003 (Figure 3a). The time-depth section of salinity during October-December from this float (Figure 3b) shows low (<32.5 psu) salinity water southeast of Sri Lanka away from the coastal region. The plausible mechanism for this low salinity water is the ESLJ; the low salinity water carried by the EICC from the northern part of the Bay of Bengal [*Shetye et al.*, 1996] is advected offshore by the ESLJ. Upper layer salinity measured by the Argo float on 4, 9 and 19 December (Figure 3c) is very similar to that of the relatively fresh Bay of Bengal waters [*Shetye et al.* 1996; *Vinayachandran et al.*, 2002]. When the location of the float is superposed on the geostrophic flow field from altimetry it was found that the float profiles in two types of currents. The float showed low upper layer salinity when it profiled within the ESLJ and showed high upper layer salinity when it was within a westward flow. This westward flow occurs south of a high in sea level off the east coast of Sri Lanka similar to that seen in Figure 2e. Thus, the Argo float data confirms that EICC bifurcates east of Sri Lanka carrying low salinity water along its path.

3.3. Ocean Color Imagery

[11] We have used ocean color images obtained by the Ocean Color Monitor (OCM) on board Indian Remote Sensing Satellite (IRS-P4) and from SeaWiFS (Sea viewing Wide Field of view Sensor). OCM data have a spatial resolution of 360 m × 236 m and the SeaWiFS (Level-3, GAC) data used here have a spatial resolution of 9 km. Images from both sensors are processed using identical algorithms and have similar representation of chlorophyll *a* (chl) concentration around Sri Lanka [*Vinayachandran et al.*, 2004]. Despite the cloud cover we have been able to obtain two images, although for different years, that capture the impact of bifurcation on chl distribution.

[12] Chl concentration map from OCM for 8 December 1999 (Figure 4 (right)) shows a band of high chl (>0.5 mg m^{-3}) along the east coast of Sri Lanka. This band is advected offshore in a southeasterly direction along the path of the ESLJ. Southward of the bifurcation point, along the coast of Sri Lanka, the chl is considerably low suggesting that the ESLJ efficiently transports chl rich water carried by EICC.

[13] On the other hand, when the EICC flows around Sri Lanka prior to its bifurcation there was no such offshore band. In 2001, the bifurcation occurred around 10 November and the weekly composite maps from SeaWiFS for 24–31 October showed that there is a band of high chl along both southern and eastern coasts of Sri Lanka (Figure 4 (left)).

4. Mechanism

[14] Generally, the basin-wide SSHA pattern in the Bay during November–December consist of a high along the periphery and low in the middle (Figure 2). The EICC is associated with a high along the coast of India. The high in the eastern Bay of Bengal extends farther offshore than in the west, due to the propagation of a Rossby wave [*Yu et al.*, 1991; *McCreary et al.*, 1996]. The excitation of this Rossby wave is due to the reflection of the fall Wyrtki jet from the eastern boundary.

[15] The process that lead to the bifurcation of the EICC can be understood by examining its evolution in time. The bifurcation occurs when an anticyclonic eddy that propagates westward ahead of the Rossy wave front hits the Sri Lankan coast. An example for this situation is shown for the year 1995 (Figure 2 (right)). An anticyclonic eddy marked by a high in sea level was noticed with its center at 86°E, 7°N on 18 October 1995 (Figure 2d). This eddy propagated westward, intensifying on its way, and met the SSH high off the Sri Lankan coast a week later and this process resulted in the bifurcation (Figure 2e). For the case of 1999, the altimeter data shows only a very weak eddy between the Rossby wave front and the high in sea level off the coast of Sri Lanka (Figure 1b). However, it is clear that the bifurcation has taken place well before the Rossby wave front abuts the Sri Lankan coast. Altimeter data show that the eddies reach the Sri Lankan coast earlier than the Rossby wave front and often there is more than one eddy propagating westward, one after the other.

[16] Altimeter data from 1992 to 2003 show that the bifurcation takes place every year the EICC exists. During

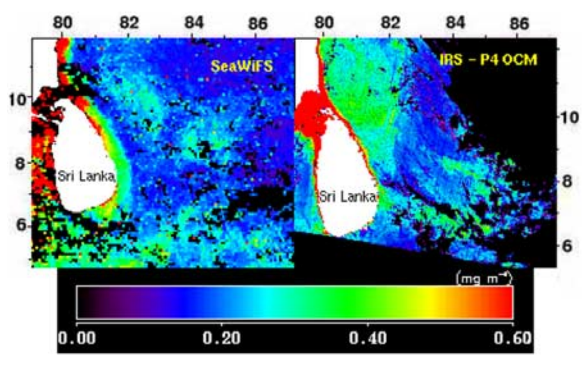

Figure 4. (right) Sea surface chlorophyll *a* (mg m^{-3}) image for 8 December 1999 from OCM and (left) weekly composite sea surface chlorophyll *a* (mg m^{-3}) image from SeaWiFS for 24–31 October 2001.

the IOD years of 1994 and 1997 the sea level anomalies were negative over most of the Bay during October–December [*Vinayachandran and Mathew*, 2003] and there was no well defined EICC during these two years. However, a high in SSHA and an anticyclonic flow around it was observed east of Sri Lanka during October–November of both 1994 and 1997. During the IOD years, the fall Wyrtki jets and, consequently, the westward propagations of the Rossby wave as well as eddies at its leading edge are weak or absent [*Vinayachandran et al.*, 1999b].

5. Summary and Conclusions

[17] The Arabian Sea and the Bay of Bengal have contrasting salinity distributions due to the large freshwater flux into the Bay of Bengal compared to the excess evaporation minus precipitation over the Arabian Sea. During the summer monsoon, the Southwest Monsoon Current intrudes into the Bay of Bengal [*Murty et al.*, 1992; *Vinayachandran et al.*, 1999a] and brings salty Arabian Sea water into the Bay of Bengal. During October–March, the EICC and the Winter Monsoon Current carries low salinity water from the Bay of Bengal into the Arabian Sea [*Shenoi et al.*, 1999; *Rao and Sivakumar*, 1999; *Shankar et al.*, 2002]. We have shown using multiple data sets that the entire EICC during November–December does not flow around Sri Lanka. Instead, it bifurcates east of Sri Lanka and the major part flows as ESLJ in an offshore direction. The bifurcation as well as the existence of the ESLJ is clearly manifested in the geostrophic flow field determined from satellite altimetry. High resolution data from OCM and OFES and Argo float observations of low salinity Bay of Bengal water southeast of Sri Lanka confirm these results. The bifurcation takes place when an anticyclonic eddy hits the east coast of Sri Lanka. The bifurcation affects the distribution of chl around Sri Lanka as well as the route of the low salinity water from the Bay of Bengal into the Arabian Sea.

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