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Bay of Bengal currents during the northeast monsoon

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Abstract. Velocity and property observations were made during February and March 1995 as part of the World Ocean Circulation Experiment (WOCE) Hydrographic Program (WHP) expedition in the Indian Ocean. The observed circulation in the upper 300 m of the ocean during the northeast monsoon is compared to the output of a high-resolution, 3-layer, nonlinear model forced by European Center for Medium Range Weather Forecasting (ECMWF) winds. The data identify several new features in the Bay of Bengal: a shelf-break coastal current in the northeast corner, an eddy and subsurface jet near the South Preparis Channel, and an eastward countercurrent extending from 80°E to the eastern boundary. The countercurrent transports high-salinity surface water from the northwest Indian Ocean into the bay, and separates the historically observed North Equatorial Current into two currents with separate sources and water properties. The data also detail the spatial structure of the South Equatorial Current and Countercurrent, and show the Equatorial Undercurrent in the eastern half of the Indian Ocean. The model compares well enough with the data to suggest that such realistic models may provide a useful temporal context for the WHP snapshot.

Introduction

The Bay of Bengal is a region of large freshwater input, high sea-surface temperature, and variable monsoonal forcing. Although historical data are sufficient to identify major features of the annual cycle of properties [*Conkright et al.*, 1994] and circulation [*Cutler and Swallow*, 1984; *Molinari et al.*, 1990] both within the bay and in the equatorial region to the south, the bay itself remains poorly observed, especially in the eastern region. *Legeckis* [1988] discusses the western boundary current using satellite observations. Recent field data [*Shetye et al.*, 1996] provide an improved picture in the western bay during the northeast monsoon, which peaks during January to March. During this period the anticyclonic circulation of the upper ocean intensifies in the northern bay; to the south, the North Equatorial Current (NEC), the South Equatorial Countercurrent (SECC), and the South Equatorial Current (SEC) are well developed.

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An introduction to the rich legacy of numerical modeling studies of the Indian Ocean can be found in *McCreary et al.* [1993] and *Vinayachandran and Yamagata* [1998], which focuses on the Bay of Bengal sector.

Measurements and Model Description

The ADCP and CTD data were taken on two consecutive legs aboard the R/V *Knorr* between 6 February and 21 March, 1995 (Figure 1a). See *Ffield* [1997] for an overview of the WOCE Indian Ocean expedition.

The hull-mounted ADCP was a 150 kHz unit manufactured by RD Instruments. Accurate position and heading data were provided by a Trimble P/Y-code and an Ashtech 3DF (four antennae) GPS receiver, respectively. Errors in the absolute velocity estimates are less than 0.02 m s^{-1} for 1-hour averages (about 20 km along the track when underway). The velocity was measured from the shallowest depth of 21 m to about 300 m. During the leg from the northeast corner of the Bay of Bengal to Colombo, the ADCP system began to fail, resulting in reduced depth range. After repair in port and testing at sea, normal ADCP operation was resumed at 2.8°N on I8N southbound.

The model results (Figure 1b) are from a high resolution simulation using the Naval Research Laboratory (NRL) nonlinear reduced-gravity Indian Ocean model with three active layers in the upper 500 m overlying an infinitely deep, quiescent fourth layer [*Bruce et al.*, 1998]. The basin-wide average thickness for the upper layer is 115 m. The model domain extends over the entire Indian Ocean north of 30°S, with a grid resolution of 0.25° in latitude and 0.37° in longitude. The model uses a high resolution basin geometry defined by the 200-meter isobath, which resolves the three primary passages between the Andaman Sea and the Bay of Bengal. The simulation was forced by the 12-hourly 1000 mbar ECMWF winds for the period 1990 through 1995, following a 35-year spinup using the *Hellerman and Rosenstein* [1983] wind stress climatology.

Results and Discussion

The most striking characteristic of the upper ocean velocity stucture is the presence of intense jet and eddy circulation patterns. The following describes the major features.

The most northerly station within the Bay of Bengal was on the continental shelf at a water depth of 107 m. Currents were weak. Just offshore of the shelf break, between 19.0°N

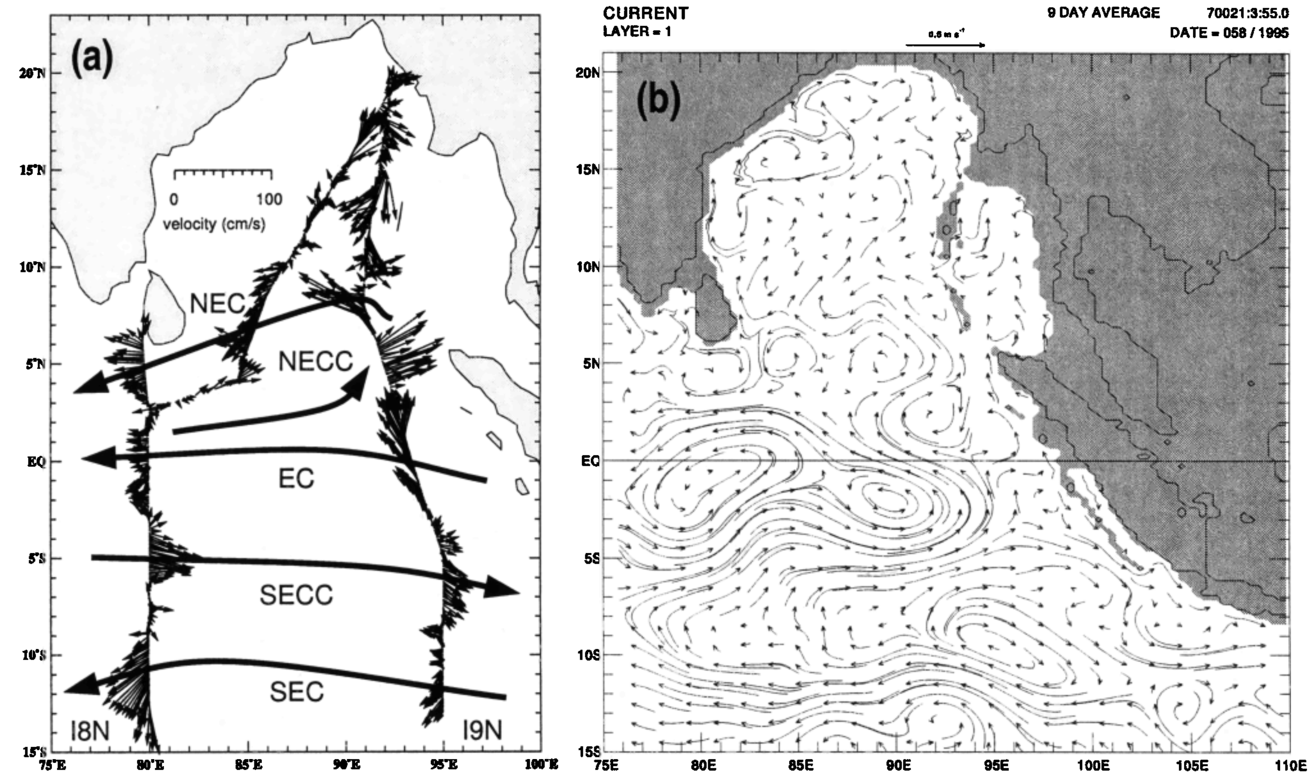

Figure 1. Near-surface currents: (a) ADCP velocity vectors averaged between 25-75 m; (b) NRL model velocity trajectories for layer 1, nominally 0-115 meters.

and 19.7°N, the current was to the east (Figure 2) with near-surface speed over 0.4 m $s^{-1}$and a transport of about 1 Sv (1 Sv = $10^6 m^3 s^{-1}$) to the east. As pointed out by an anonymous reviewer, the current may be part of the annual cycle along the eastern boundary [*McCreary et al.*, 1993]. The NRL model run shows the current developing about 12 February and continuing through 5 March, and suggests that the feature is directly forced and deterministic.

A striking feature, the Preparis Eddy, is centered at 14.7°N, 91.5°E, just west of the South Preparis Channel (Figure 3). The eddy is subsurface intensified with a maximum speed of 0.8 m s^{-1} at 140 m; has a diameter of 300 km at 150 m; and is associated with a larger surface gyre in the top 100 m, with a diameter of nearly 700 km. The transport in the upper 100 m associated with the larger-scale gyre is 6 Sv. The transport between 100–200 m depth associated with the subsurface eddy is 3 Sv for the northern half and 6 Sv for the southern half. A possible explanation could be a jet flowing out of the Andaman Sea through the South Preparis Channel, which has a sill depth about 400 m. The south edge of the westward flowing jet has a salinity anomaly of -0.60 psu and an oxygen anomaly of +15.4 μmol kg^{-1} at 17.20°C and depth 140 m, suggesting a source other than the northeast Bay of Bengal. The NRL model shows a less intense feature spinning up in layer 1 on 24 February and continuing until mid-March 1995. For the 5-year period, 1991-1995, the eddy appeared in 1992, 1993 and 1995. In 1992 and 1993 it was related to a sub-surface jet and was sub-surface intensified. However, in 1995 it was surface-trapped and was not associated with a sub-surface jet. The eddy does not seem to be a simple annual event.

From 9°N to 10°N at 91°E there is an eastward flow of 0.4 m $s^{-1}$with the high salinity signature of northwest Indian Ocean water. It may be entering the Andaman Sea or it may be a recirculating eddy on the northern edge of the NEC.

The NEC is apparent at three longitudes (Figure 1) with transport in the upper 100 m ranging from 8-10 Sv consistent with results of [*Schott et al.*, 1994]. At 91°E the variation of near-surface salinity with latitude suggests recirculation eddies on both the north and south sides of the NEC. On all three sections the NEC has higher salinity (34.5 psu) along its southern edge, representing the northwest Indian Ocean source (Figure 4). South of Sri Lanka the salinity is reduced (33.0–33.5 psu) along the NEC's northern half representing a mixture of the fresher Bay of Bengal water with the northwest Indian Ocean water.

Our observations show eastward flow, which we tentatively label the North Equatorial Countercurrent (NECC), extending from 80°E to 92°E. The current transports a local surface salinity maximum (34.5 psu) along its northern edge, indicating its northwest Indian Ocean source (Figure 4), and intensifies to the east. Both the northern and southern parts of the current at 92°E seem to be associated with recirculation eddies as shown by the velocity vectors and the surface salinity distribution. Part of the NECC may enter the Andaman Sea and part must retroflect into the NEC east of our observations. The section from 85°E to 80°E near 3.5°N goes along the northern edge of the NECC. Along 80°E between 2.8°N and 2°N the ADCP shows eastward flow near the surface. This eastward flow (the NECC) broadens with depth and extends from 1.5°N to 4°N at 100 m. Note that

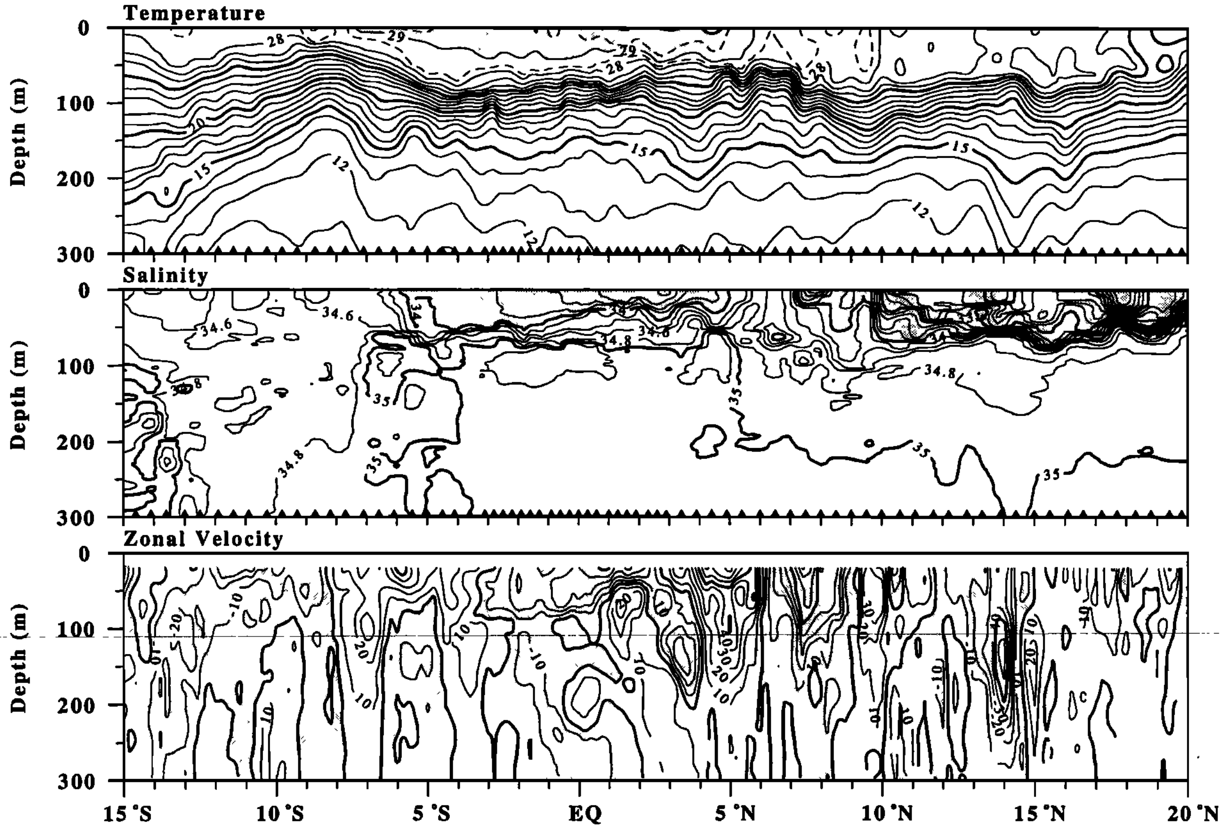

Figure 2. Properties along the I9N eastern line: temperature, salinity, and u component of velocity (positive eastward, cm/s). Shaded regions are negative, and the contour interval is 10 cm/s.

the NECC is very narrow at 80°E compared with the eastern side of the basin. At 80°E it may be an occasional feature pinched off to the south of Sri Lanka between the NEC and the Equatorial Current (EC). As an alternative interpretation, the NECC at 92°E could be simply part of an intense eddy, disconnected from the weak eastward flow west of 85°E. The high surface salinity would then be attributed to upwelling and diapycnal mixing in the core of the eddy. While the NRL model does not show the NECC at 80°E, it does produce a weak countercurrent trough with eastward currents between 3°N and 5°N and from 83°E to the eastern boundary, indicating a tendency for the NEC to retroflect to the east south of Sri Lanka, consistent with model circulation in *Vinayachandran and Yamagata* [1998].

To the south of the NECC, we observed the EC, with a westward transport above 100 m of 5 Sv at 80°E and 7 Sv at 91°E. The surface salinity is consistently lower in the east and higher in the west. *Cutler and Swallow* [1984] and *Molinari et al.* [1990] show the EC, but do not distinguish it from the NEC. The NRL model represents the EC as a feature associated with the retroflection of SECC flow across the equator (Figure 1b), a finding also suggested by the drifter tracks shown in *Molinari et al.* [1990].

Below the EC we observed the eastward flowing Equatorial Undercurrent (EUC) also noted in *Talley and Baringer* [1997]. At 80°E and 93°E the EUC extends over the depth range 60–140 m, has peak speed of 0.4 m s^{-1} and a transport of 1 Sv. At 93°E the EUC is shifted north of the Equator, extending from 0.7°N to 2.3°N.

To the south of the EC we observed the eastward SECC and the westward SEC. The transports of both are 50% higher at 80°E than at 95°E (Figure 4). Our measurements add spatial resolution to the historical picture developed by *Cutler and Swallow* [1984], *Molinari et al.* [1990], and *Conkright et al.* [1994] for this season. The surface ve-

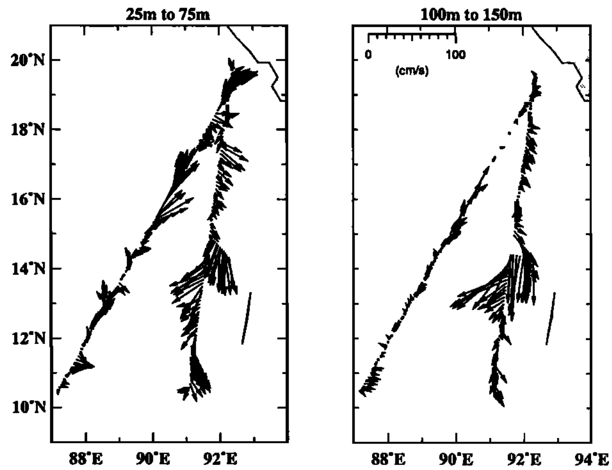

Figure 3. Layer-averaged velocity in the eastern Bay of Bengal, showing the Preparis Eddy.

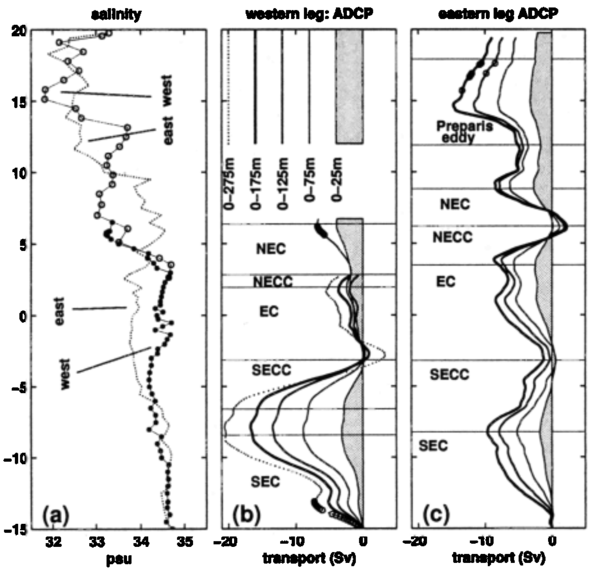

Figure 4. (a) Average salinity (psu) from 10–40 m from the western leg (circles, end of I9N and all of I8N) and eastern leg (dotted, eastern part of I9N). ADCP transport (Sv) integrated from the south for the (b) western leg and (c) eastern leg, assuming constant velocity from 25 m to the surface, and linearly interpolating across missing data (small circles).

locity and property distributions suggest recirculation eddies at the northern and southern boundaries of the SECC and SEC. In the region south of the Equator, the NRL model shows local eddies and elongated recirculation features which appear consistent with our velocities. The effect of these features on the Indonesian Throughflow Plume are discussed in *Gordon et al.* [1997].

Maps of the near-surface temperature and salinity distributions within the Bay of Bengal appear in *Conkright et al.* [1994]. The maps do not resolve the effects of the NECC and the EC on the property distributions due to smoothing and a lack of historical high resolution observations. Our data provide details of the vigorous circulation pathways which bring high salinity water into close proximity with the fresh, surface water within the bay, and suggest that the stirring processes occur in very shallow layers (Figure 2).

In the mean model solution over the cruise period (not shown), the NEC and EC are fed by cross-equatorial, retroflected transport from the SECC. The circulation shown in Figure 1b contains the essential elements of the mean pattern. The model EC's latitude range and the flow south of Sri Lanka differ somewhat from the observations. However, given the quasi-synoptic nature of the sampling, the limitations of the model (particularly the vertical and horizontal resolution), the uncertainty in the model forcing and the high variability in this region, the comparison of the observations and the model results is encouraging.

An observational goal for the future is to determine the temporal variability of the observed features and pathways.

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