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Observations of barrier layer formation in the Bay of Bengal during summer monsoon

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[1] Time series of temperature and salinity in the upper ocean, measured at 17°30′N, 89°E in the northern Bay of Bengal, from 27 July to 6 August 1999 captured an event of upper layer freshening. Initially, the upper layer that is homogeneous in both temperature and salinity was about 30 m deep. Subsequently, the arrival of a freshwater plume caused the depth of the mixed layer to decrease to about 10 m and the salinity in the surface layer by about 4 psu. The plume led to the formation of a new halocline and hence a barrier layer within the upper 30 m of the water column. The ensuing ocean-atmosphere interaction was restricted to the new thinner mixed layer. The cooling that was restricted to the mixed layer led to an inversion in temperature amounting to 0.5°C just below the mixed layer. The source of the plume is traced to freshwater from river discharge and rainfall that was advected by Ekman flow as a 15 m thick layer. This study suggests that wind-driven circulation is crucial in determining the path of freshwater in the Bay of Bengal. The fresh water affects the sea surface temperature and ocean- atmosphere coupling through the dependence of the depth of the mixed layer on salinity. *INDEX TERMS:* 4572 Oceanography: Physical: Upper ocean processes; 4536 Oceanography: Physical: Hydrography; 9340 Information Related to Geographic Region: Indian Ocean; *KEYWORDS:* Bay of Bengal, barrier layer, mixed layer, summer monsoon, freshwater plume, Ekman flow

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1. Introduction

[2] Several monsoon lows and depressions, that contribute substantially to the summer monsoon rainfall of the Indian subcontinent, form over the Bay of Bengal and then move towards the land [*Gadgil*, 2000]. The formation of such weather systems depend on the convective activity over the Bay of Bengal which is affected by conditions of the ocean underneath. It has been shown that high convection in the monsoon regions is restricted to that part of ocean having sea surface temperature (SST) in excess of 27.5°C [*Gadgil et al.*, 1984]. The SST in turn is determined by upper ocean processes such as surface heat fluxes, advection and mixing. Further, observations made during Tropical Ocean Global Atmosphere-coupled ocean atmosphere response experiment (TOGA-COARE) suggest that salinity considerations are important in the oceanic mixed layer because salinity often is the decisive parameter for the depth of the mixed layer in the ocean (for a review see *Godfrey et al.* [1998]). Clearly, it is essential to understand the upper ocean thermohaline structure, its variability and the underlying processes to appreciate ocean-atmosphere coupling over monsoon regions.The Bay of Bengal Monsoon Experiment (BOBMEX) was envisaged with this goal.

[3] The Bay of Bengal is forced locally by seasonally reversing monsoon winds and remotely by the winds in the equatorial Indian Ocean [*McCreary et al.*, 1993]. In addition, the Bay receives a large quantity of freshwater from both rainfall and river runoff from the bordering countries. Annually, the major rivers Irrawaddy, Brahmaputra, Ganga and Godavari discharge about 1.5×10^{12} m^3 of fresh water into the Bay of Bengal and rainfall ranges between 1 m and 3 m [see *Shetye et al.*, 1996]. The freshwater influx into the Bay of Bengal maintains 'a barrier layer' (the layer between the base of the mixed layer and the top of the thermocline) which has a thickness of 25 m during the summer monsoon [*Sprintall and Tomczak*, 1992]. Hydrographic surveys carried out along the Indian coast during southwest [*Shetye et al.*, 1993] and northeast [*Shetye et al.*, 1996] monsoons show the effect of freshwater in the upper ocean. During the southwest monsoon, a fresh water plume detached from the coast by a 40 km wide upwelling band was observed. During the northeast monsoon, the low salinity water was found along the entire Indian east coast as a narrow current hugging the entire coastline. During both seasons, the upper ocean stratification in the northern Bay of Bengal was found to be dominated by salinity rather than temperature. From a time

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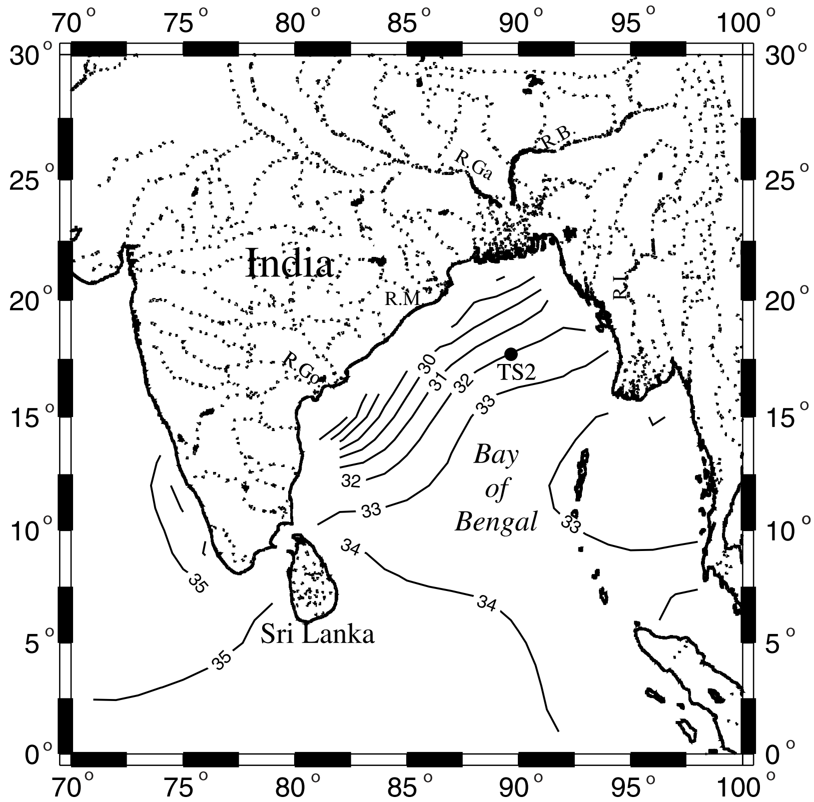

Figure 1. The map of the study area. The dotted lines on the land show rivers. Several large and small rivers discharge into the Bay of Bengal. Rivers Godavari (R.Go.), Mahanadi (R.M.), Ganga (R.Ga.), Brahmaputra (R.B.), and Irrawady (R.I.) are marked in the figure. The ORV Sagar Kanya was at the location TS2 (17°30′N, 89°E) from 27 July to 6 August. The contours are climatological sea surface salinity for the month of July [*Conkright et al.*, 1998].

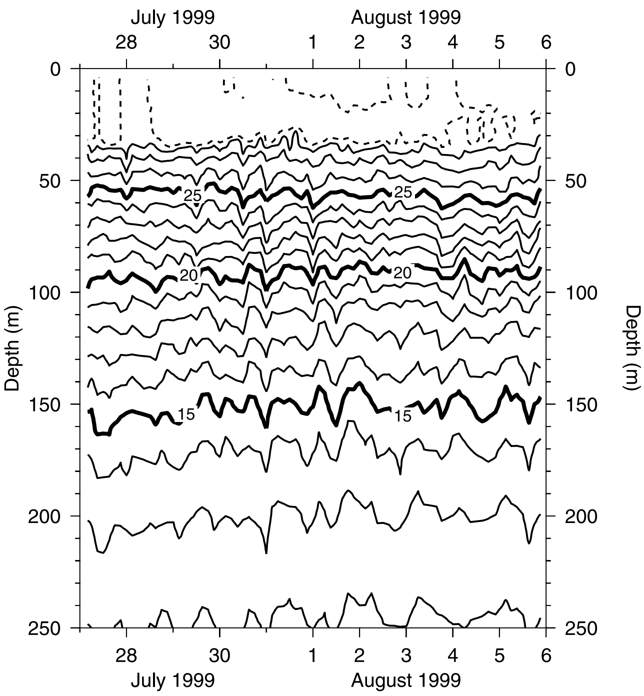

Figure 2. Time depth section of temperature at TS2. Contour interval is 1°C. Every fifth contour is shown by thick lines. The 28.5°C isotherm is shown by dashed contour.

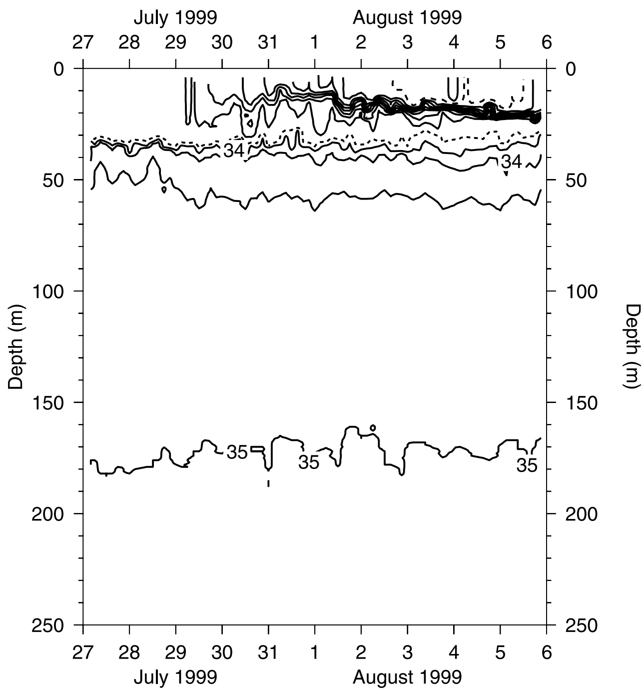

Figure 3. Time depth section of salinity at TS2. Contour interval is 0.5 psu. The 29 and 33 psu contours are shown by dashed and dotted lines respectively.

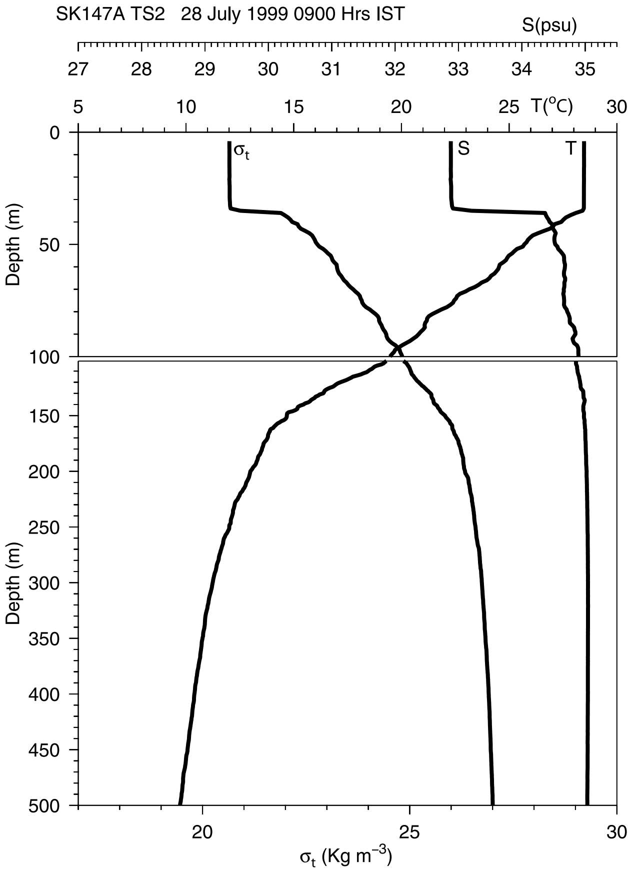

Figure 4. Vertical profiles of temperature, salinity and density on 28 July at 0900 hours IST.

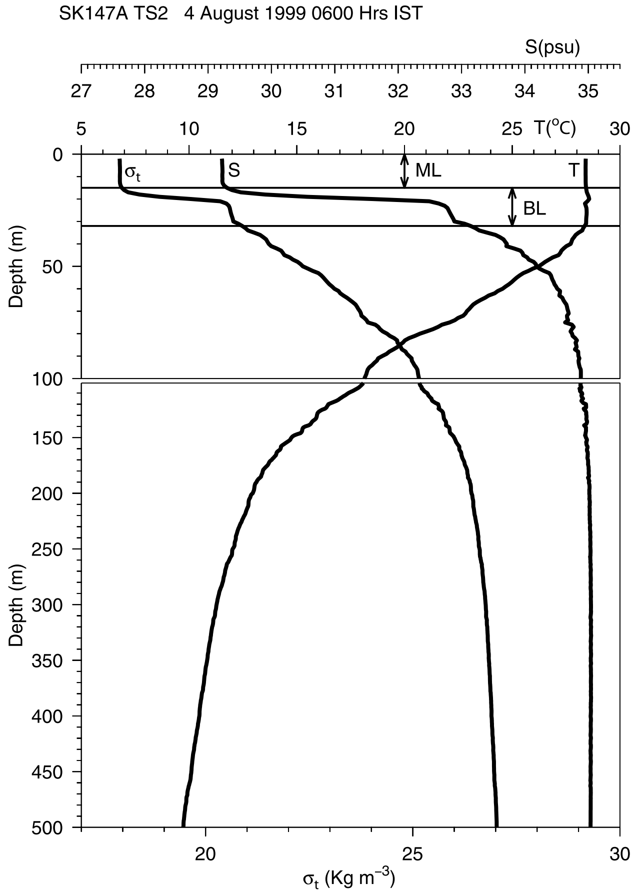

Figure 5. Vertical profiles of temperature, salinity and density on 04 August 1500 at 0600 hours IST. ML and BL indicates mixed layer and barrier layer respectively.

series of hydrographic observations conducted in the northern Bay of Bengal at 20°N,89°E during August–September, 1990, *Murty et al.* [1996] found that the mixed layer based on a temperature criterion is deeper than that using density. The region with relatively fresh water with high SST appears to be an excellent breeding ground for the formation of monsoon depressions [*Sanil Kumar et al.*, 1994; *Murty et al.*, 2000]. In the open bay, the sea surface salinity increases from about 20 psu (practical salinity units) at the head of the bay to about 34.5 psu at 5°N during summer monsoon [*Murty et al.*, 1992]. Higher salinity in the south is caused partly due to the intrusion of the southwest monsoon current into the Bay of Bengal which brings saltier Arabian Sea water [*Murty et al.*, 1992; *Vinayachandran et al.*, 1999].

[4] Salinity effects on the tropical upper ocean are probably best observed in the western equatorial Pacific Ocean during TOGA-COARE. In the West Pacific, after a spell of rain, the salinity of the upper ocean decreases and consequently the mixed layer shallows. The decrease in salinity due to rainfall appears to be of the order of 0.2 psu [*Lukas and Lindstrom*, 1991]. In contrast, climatological data [*Conkright et al.*, 1998] suggest that combined effect of rainfall and river discharge reduces the salinity in the northern Bay of Bengal from May to July by as much as 5 psu. During August–September 1990, *Murty et al.* [1996] observed a decrease of 3 psu in the surface salinity. The winds over the Bay of Bengal during summer monsoon is quite strong unlike the light wind conditions in the western

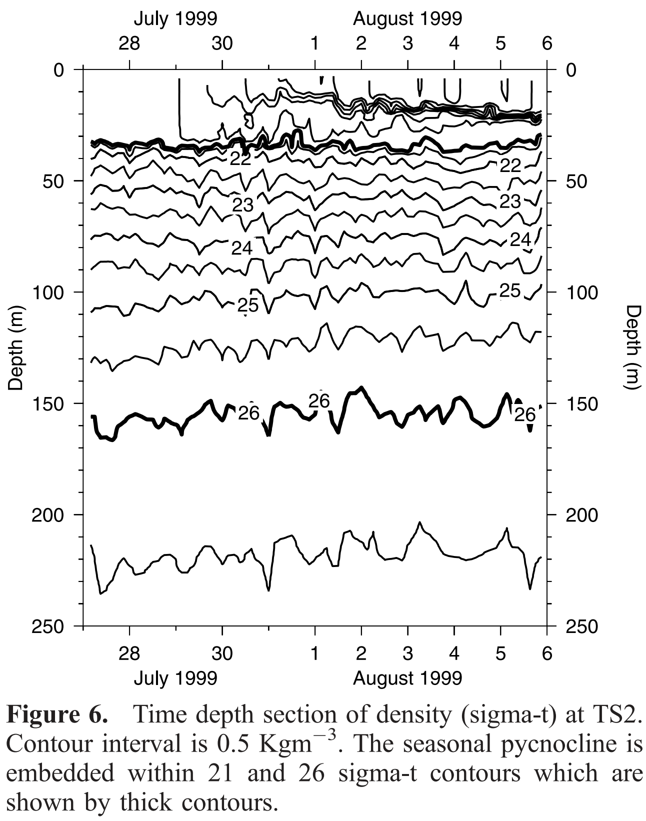

Figure 6. Time depth section of density (sigma-t) at TS2. Contour interval is 0.5 Kgm^{-3}. The seasonal pycnocline is embedded within 21 and 26 sigma-t contours which are shown by thick contours.

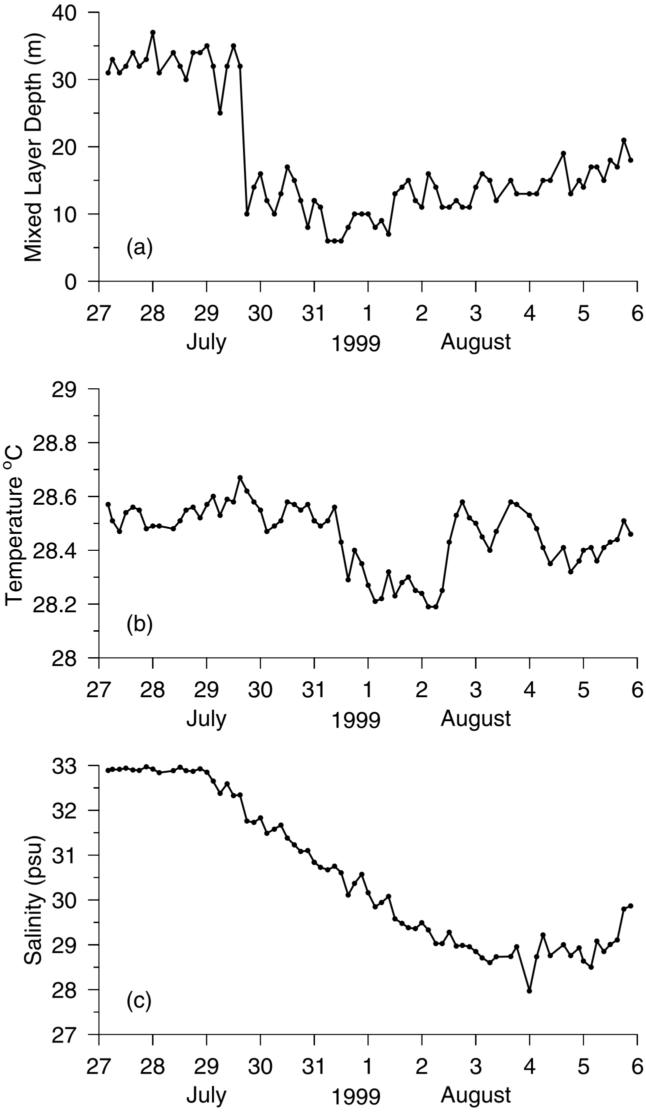

Figure 7. The variation of (a) mixed layer depth (b) temperature at 5 m and (c) salinity at 5 m at TS2.

equatorial Pacific. Under these conditions does the upper ocean in the Bay of Bengal behave in a manner similar to the western equatorial Pacific? Does the freshening of the upper layer insulate it by means of barrier formation? The observations that are crucial to address such questions have been lacking hitherto.

[5] A major objective of BOBMEX was to collect high quality data on atmospheric and oceanic variables during different phases of the summer monsoon. The scientific background, objectives and details of the experiment have been described by *Bhat et al.* [2001]. One of the scientific goals of BOBMEX was to document and understand the thermohaline structure of the upper ocean under different phases of atmospheric convection and the underlying mechanisms. In order to achieve this, time series of CTD casts were carried out at a fixed location (17°30′N, 89°E; hereafter referred to as TS2) in the northern Bay of Bengal (Figure 1). These observations were successful in capturing an event of arrival of fresh water at this location and the consequent reduction in salinity by more than 4 psu. The

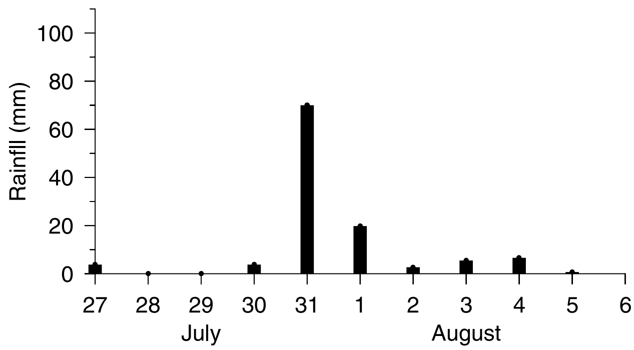

Figure 8. The rainfall (mm) measured at TS2.

objective of this paper is to describe this event and its implications to the upper ocean characteristics. The observations are described in the next section. Relative roles of rainfall and river discharge in causing the reduction in salinity and the related ocean circulation processes are examined in section 3. Implications of the newly formed fresh layer to the upper ocean thermal structure is discussed in section 4 and major conclusions are listed in section 5.

2. Observations

[6] Figure 1 shows the location of observations in the northern Bay of Bengal. 75 profiles of upper ocean temperature and salinity were measured using a Sea Bird (SBE plus 9/11) CTD at TS2 from 27 July to 6 August 1999 (Phase I) during the cruise 147A of *ORV Sagar Kanya*, and 66 profiles were measured during 13–23 August 1999 (Phase II) during the cruise 147B. The temperature sensor on the CTD system had an accuracy of ±0.001°C and the salinity was measured to an accuracy of ±0.003 psu. The measurements were made up to a depth of 1000m at 3 hourly intervals and data were averaged into 1 m depth-bins. The data collected during Phase I is used for the present study. For a complete list of all oceanic and

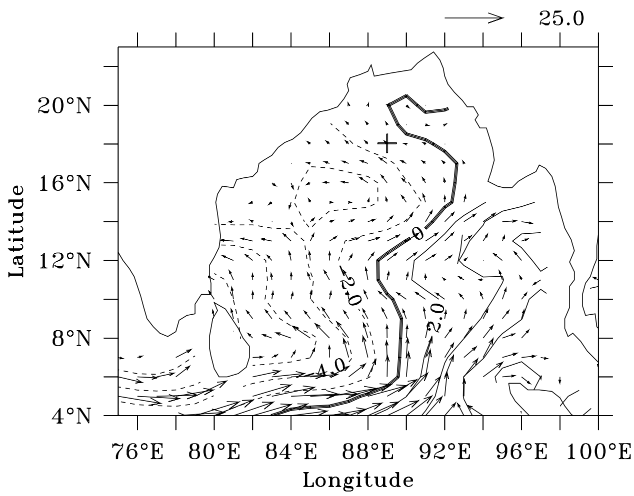

Figure 9. The sea surface height anomalies (contours in cm) and geostrophic currents (vectors in cm s^{-1}) from the TOPEX/Poseidon (Cycle 253; Start date 27 July 1999) altimeter data. The cross indicates location of TS2.

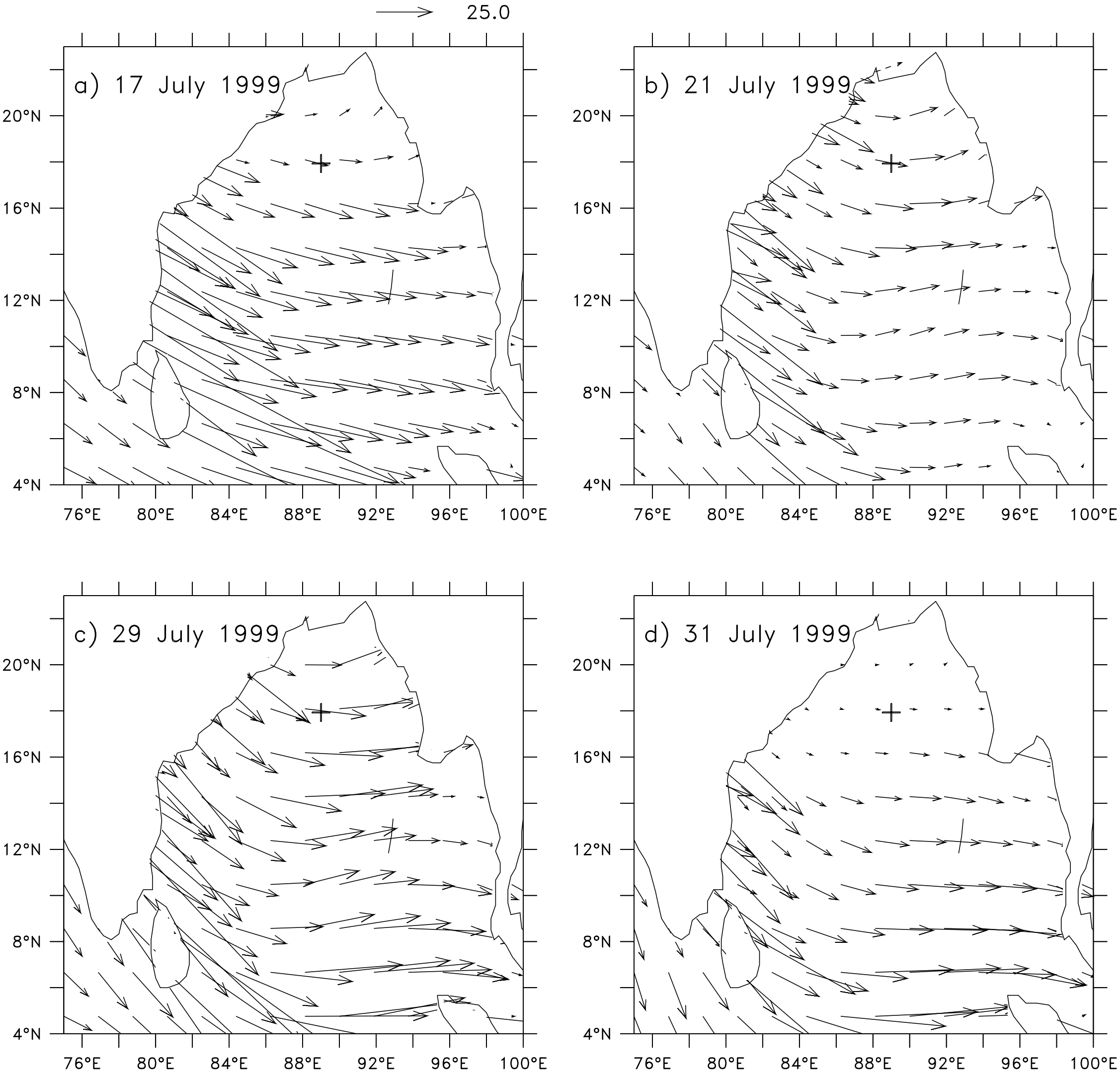

Figure 10. The Ekman drift (cm s^{-1}) calculated from the NCEP daily winds for (a) 17 July 1999, (b) 21 July 1999, (c) 29 July 1999 and (d) 31 July 1999. The cross in all panels indicates location of TS2.

atmospheric variables measured during BOBMEX please refer to *Bhat et al.* [2001].

2.1. Isothermal Layer and the Thermocline

[7] Figure 2 shows the time-depth section of temperature at TS2. The temperature profiles show an isothermal layer which is about 30 m deep with a temperature of about 28.5°C. This layer shallowed by about 5 m towards the end of Phase I. The 28.5°C isotherm marks the base of the isothermal layer (Figure 2) and below this layer the seasonal thermocline exists in which the temperature drops by 15°C over a depth range of 200 m. Below 200 m the temperature decreases gradually. There are oscillations in the water column below the isothermal layer. A preliminary analysis shows that the spectrum of temperature in the thermocline has a peak at 12 hours. These oscillations could be a manifestation of internal tides.

2.2. Monsoon Halocline and the Barrier Layer

[8] The salinity structure (Figure 3) showed dramatic fluctuations during the initial stages of the observation period. During the first two days, the isohaline layer having a salinity of about 33 psu coincided with the isothermal layer. The seasonal halocline that exists below has two regimes; in the upper part of the halocline the salinity increases rapidly for about 5 m by 1 psu and below this layer the salinity increases at a slower rate of 1 psu over a depth of 20 m. Below the seasonal halocline the salinity remains close to about 35 psu. Such a profile measured on 28 July at 0900 hours IST is depicted in Figure 4.

[9] The decrease in near surface salinity started on 29 July and is confined to the isothermal layer that was 30 m deep initially. The fresh water that arrived at TS2 does not seem to have penetrated into the seasonal halocline that existed prior to 29 July (Figure 3). The freshwater formed a new halocline within the isothermal layer (Figure 2). For convenience we call this new halocline, the monsoon halocline of the Bay of Bengal (MHB). Thus, within the isothermal layer three regimes of salinity exists. The upper isohaline layer which has uniform salinity, an MHB in which the salinity increases rapidly and a layer below the MHB in which the salinity increases more gradually. An example of such a profile measured on 04 August at 0600

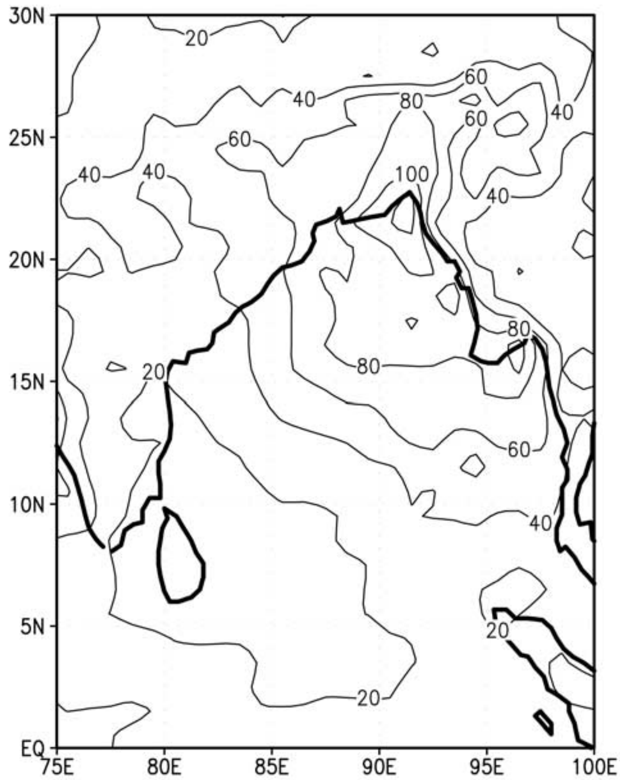

Figure 11. Distribution of rainfall (cm) received in the Bay of Bengal from 1 June 1999 to 29 July 1999 [*Huffman et al.*, 2001].

hours IST is shown in Figure 5. The thickness of the MHB varies between 10–15 m and the salinity increases by over 4 psu from its top to the bottom. The MHB is separated from the seasonal halocline by a region in which salinity increases by about 0.5 psu over a depth of 15 m.

[10] The time depth section of density (Figure 6) clearly demonstrates the importance of salinity on the vertical stratification. The density structure also shows the effect of MHB within the isothermal layer and its separation from the seasonal pycnocline. Below the halocline the density appears to be determined primarily by temperature variations.

[11] Based on the TOGA-COARE observations from western equatorial Pacific Ocean, the barrier layer is defined as a layer between the base of the mixed layer and the top of the themocline [*Lukas and Lindstrom*, 1991]. Application of this definition to the Bay of Bengal gives a barrier layer which is about 25–30 m thick that includes the MHB and the region of weaker salinity gradient below. The vertical gradient of salinity observed in the barrier layer of the western equatorial Pacific is 0.01 psu m^{-1} [*Lukas and Lindstrom*, 1991] or 0.02 psu m^{-1} [*Ando and McPhaden*, 1997]. In the Bay of Bengal, the layer between the base of the MHB and the top of the thermocline has a salinity gradient of 0.03 psu m^{-1} while MHB has a salinity gradient as high as 0.27 psu m^{-1} (Figure 5).

2.3. Mixed Layer

[12] Various criteria are found in the literature for determining the depth of the upper homogeneous layer in the ocean [see *Kara et al.*, 2000]. Historically, this was defined as the layer in which temperature is nearly uniform. The TOGA-COARE observations have shown that the isothermal layer is not always well mixed in density due to the influence of salinity. In such cases a criterion based on density is ideal. Two types of definitions can be found in literature for determining the depth of the mixed layer (MLD). In the first, the depth at which density changes by a fixed value from the surface is chosen as the MLD. The second method relies on the observation that in the ocean there is a layer in which the properties change rapidly immediately below the mixed layer. That is the case in the Bay of Bengal as can be seen from Figures 2–6. Therefore we have adopted this gradient method. A practical difficultly that many of the first CTD measurement were 2–5 m below the sea surface (due to operational safety of the equipment) further encouraged us to use this method. We have defined the MLD as the depth at which the vertical gradient of sigma-t exceeds by 0.05 Kg m^{-4}. The MLD so determined is shown in Figure 7a. The rapid decrease in the MLD consequent to the freshening of the upper layer is evident in this figure. For the profiles shown in Figures 4 and 5 the MLD was obtained as 34 m and 15 m respectively. The mean MLD for the entire observation period is 18 m with the mean before the freshening being 32 m and after the freshening 12 m.

[13] The temperature and salinity of the upper mixed layer is shown in Figures 7b and 7c respectively. Their respective values at 5 m is chosen for this purpose as the CTD measurement did not always start at the sea surface. The temperature stayed close to 28.5°C except during the cloudy and rainy period of 31 July - 2 August when it dropped to 28.2°C (Figure 7b). The salinity started decreasing on 29 July. The surface salinity at 0000 hrs IST on 29 July was 32.84 psu and this decreased to 31.826 psu within 24 hours. The decrease in salinity continued till the salinity fell to 28.6 psu on 3 August. The salinity remained within 28.6–30.0 psu from 0300 hours IST on 1 August to 0000 hours on 6 August with an exceptional value of 27. 96 psu measured on 4 August at 0000 hrs (Figure 7c).

3. Processes

[14] The decrease in surface salinity is due to the freshwater input. There are two sources of freshwater into the Bay of Bengal: first is the rainfall and the second is the river discharge. The local rainfall at TS2 was measured using an automatic rain gauge [*Bhat et al.*, 2001] and is shown in Figure 8. It rained slightly during 30 July and 70 mm of rain occurred during 31 July. The freshening of the layer began on 29 July. For a 100 mm of daily rainfall the salinity change in a mixed layer of 15 m is about 0.2 psu. The salinity changes induced by local rainfall are much smaller than the observed decrease in salinity. The vertical exchange can not decrease salinity as the salinity increases downward in the water column. Therefore we conclude that the freshening was caused by the advection of low salinity water from elsewhere.

[15] In order to delineate the pattern of surface circulation that could advect low salinity water to TS2 we first examined the altimeter data from TOPEX/Poseidon [*Tapley et al.*, 1994]. The sea surface height (SSH) anomalies and the geostrophic currents calculated from them (Figure 9)

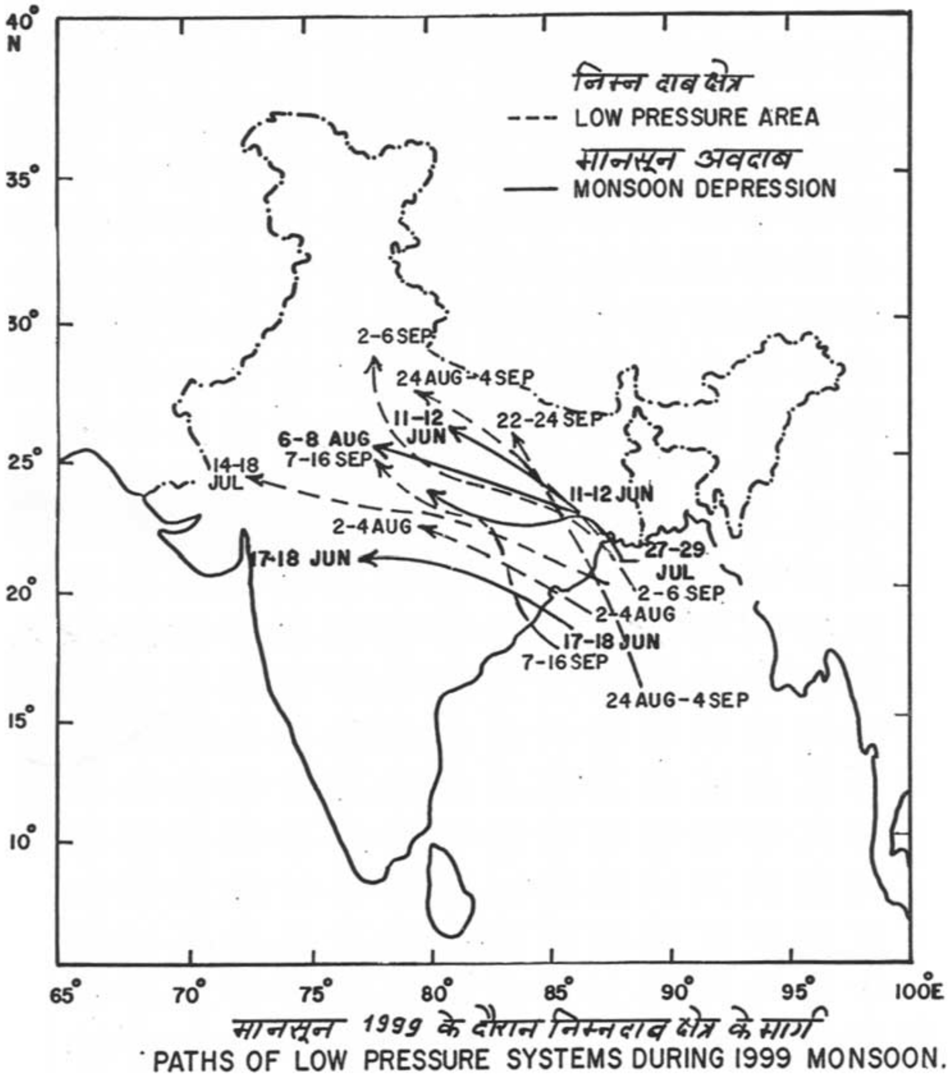

Figure 12. Tracks of monsoon low and depression systems formed over the Bay of Bengal during the summer monsoon of 1999. Low and depression on a synoptic weather chart with 2 mb pressure contour interval is defined as weather systems with one and two to three closed contours respectively. Note that the systems of 14–18 July and 27–29 July have only ending and beginning labels respectively. Source: India Meteorological Department.

indicate that the geostrophic flow is towards north. The salinity at the surface in the Bay of Bengal during summer (Figure 1) increases towards south [*Murty et al.*, 1992]. Obviously the observed decrease in salinity at TS2 is not caused by the northward geostrophic flow suggested by altimeter data. Recently, while studying the monsoon current system in the north Indian Ocean *Shankar et al.* [2002] found that the open ocean currents in the Bay of Bengal during summer monsoon are predominantly Ekman flow. Therefore we calculated the Ekman drift [*Shankar et al.*, 2002; *Pond and Pickard*, 1983] using the NCEP [*Kalnay et al.*, 1996] daily winds which is shown in Figure 10. The Ekman flow (Figure 10c) suggests that the low salinity water can be advected eastward from the coast of India to the location of the study area. During the summer monsoon several large and small rivers discharge freshwater into the Bay of Bengal. Of these the major ones are Godavari along the western coast of the Bay, Ganga and Brahmaputra in the north and Irrawaddy in the east (Figure 1). *Shetye et al.* [1993] observed a freshwater plume of river discharge origin separated from the coast by an upwelling band caused by local alongshore winds. Though the percentage contribution of rainfall and river discharge into the river plume is not known it is believed that major part comes from the discharge by the Ganga-Brahmaputra river system [*Shetye et al.*, 1993]. The river Ganga alone discharges about 7×10^{10} m^3 of water into the Bay of Bengal during June and July. The northern Bay of Bengal also receives rainfall from monsoon depressions. Daily rainfall data from the Global Precipitation Climatology Project (GPCP) suggest that north of 15°N the Bay of Bengal received between 80–100 cm of rainfall during June–July, 1999 (Figure 11). We, therefore, conclude that the low salinity water observed at TS2 is a result of advection by the Ekman flow of the fresh water brought into the Bay of Bengal by river discharge and rainfall over the basin during June – July.

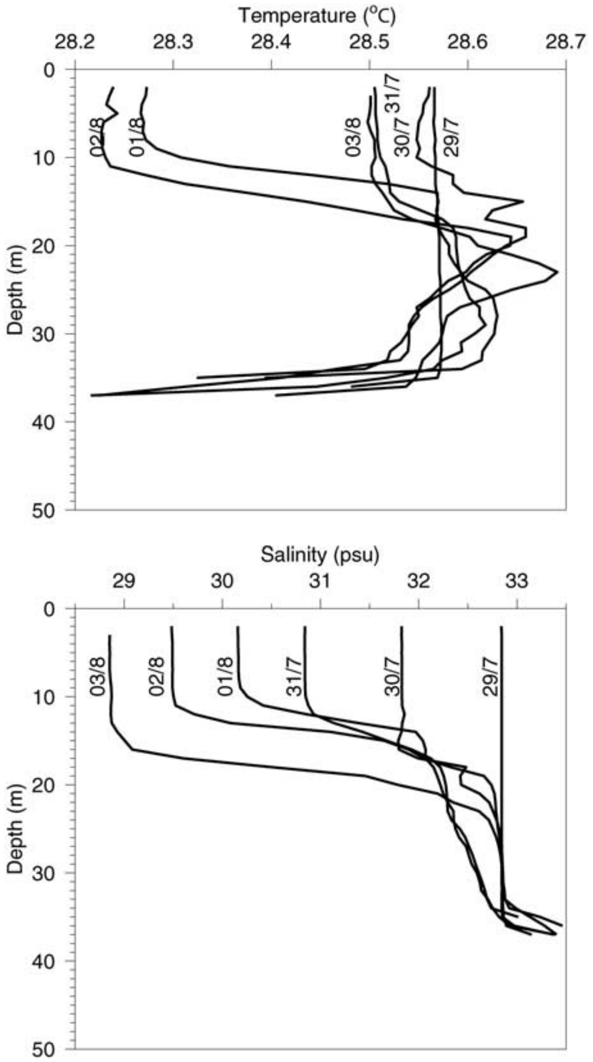

Figure 13. (top) Evolution of temperature and (bottom) salinity at TS2 during the arrival of the freshwater plume. Profiles at 0000 hrs IST are shown.

[16] The Ekman currents derived from the NCEP daily winds had similar flow pattern during the 15–30 July 1999 period though its strength varied. (Figure 10). From 31 July to 02 August the Ekman flow was found to be weak but it revived on 03 August. For an advective velocity in the range of 25–50 cm s^{-1} the river plume in the coastal region which is at a distance of about 500 km from TS2 would take between 12–23 days to reach the location of TS2. This time can be considerably shorter for the freshwater received in the region north of TS2 from rainfall (Figure 11) and for the river plume that has already moved a certain distance offshore.

[17] What determines the timing of the arrival of the fresh plume at TS2? The winds over the Bay are southwesterly from May through September [*Hellerman and Rosenstein*, 1983] and the river discharge attains its peak during July–August. The Ekman flow may be transporting the fresh water into the open ocean as soon as it is available. The sudden drop in salinity at TS2 during 29 July-3 August, however, favors a weather event during which winds suddenly strengthened. During Phase I, two weather systems formed in the northern Bay of Bengal north of TS2 (Figure 12). A monsoon depression was present during 27–29 July and a low pressure system during 2–4 August (Figure 12). The winds recorded at TS2 exceeded 15 m s^{-1} during these periods. It is very well possible that the high winds during these periods and the associated increase in Ekman transport played a crucial role in pushing the freshwater plume away from the coastal region and to the location of TS2 in the open Bay of Bengal. It is interesting to note that such weather systems that occurred prior to the observations period was during 11–12 June and 17–18 June which are too early for the rivers or rainfall to have attained significant accumulation of freshwater and that the low pressure system during 14–18 July (Figure 12) had much weaker Ekman transport (Figure 10a).

4. Implications

[18] The evolution of temperature and salinity at TS2 as the freshwater plume arrived are shown in Figure 13. The thickness of the plume is about 15 m. This is evident from the drop in salinity of the upper 15 m of the water column. The gradient below the isohaline layer is a result of mixing between the low salinity water of the plume and the more saline water underneath. This gradient increases till the lowest salinity water arrives. After 1 August, the salinity below the gradient tends to revert to its value as on 27 July. This is most probably due to the generally northward geostrophic flow that is prevalent below the Ekman layer which suggests that there is a two layer flow in the upper 30 m in which the low salinity water moves eastward in the upper 15 m and a geostrophic layer in which the saltier water moves northward.

[19] The temperature of the 15 m water column reduces initially after the arrival of the plume but warms thereafter (Figure 13). Since the mixed layer was initially 30 m deep and the changes after 29 July are restricted to the upper 15 m, a temperature inversion developed between 15–30 m (Figure 12). The maximum temperature inversion of about 0.5°C was observed on 2 August. On 1 August the ocean lost about 50 Wm^{-2} to the atmosphere and on 2 August there was a net heat gain of similar magnitude [*Bhat*, 2001]. For a 10m water column in the Bay of Bengal, this implies a temperature change of 0.1°C. The observed cooling on 1 August is less than this value and the much larger warming on 2 August lead us to speculate that the advection of fresh water causes slight warming at TS2. *Bhat* [2001] calculated the SST changes due to net surface heat flux and concluded that horizontal advection need to be considered in order to explain the observed temperature changes during the 1–3 August. An attempt to estimate the effect of local rainfall on SST was futile as the T-S points did not fall on the mixing line between rainwater at wet bulb temperature and the sea water.

[20] In the Pacific, following a spell of rain the salinity of the surface water decreases leading to the formation of a salt stratified barrier layer just below the upper mixed layer. The barrier layer insulates the upper mixed layer from mixing with the water below and traps the heat exchange with the atmosphere except the penetrating component of solar radiation. One-dimensional model results [*Anderson et al.*, 1996] show that the warming rate of SST can decrease when

the mixed layer thickness decreases because a thinner layer absorbs less solar radiation [*Godfrey et al.*, 1998]. Thus in regions where solar radiation is a large term in the net surface heat flux, the barrier layer may not affect the rate of change of the temperature of the surface mixed layer particularly when the depth of the mixed layer is small. In the Bay of Bengal during cloud free conditions this could be the case as the solar radiation exceeds 800 Wm^{-2} at noon [*Bhat*, 2001]. During cloudy days, however, when there is a net heat loss at the sea surface the presence of the barrier layer affects mixed layer temperature. The cooling that is seen in Figure 13 indicates that during cooling events the barrier layer confines major portion of the local air-sea heat exchange to the upper mixed layer. Since upper layer temperature is influenced by several processes including local rainfall, advection, interaction with the inversion layer and penetration of solar radiation it is necessary to conduct detailed analyses of the heat budget and model experiments to explain the observed fluctuations of upper layer temperature.

5. Summary and Conclusions

[21] As a part of BOBMEX, during the summer monsoon of 1999, the upper ocean hydrography was monitored in the northern Bay of Bengal. The observations captured a spectacular event in which a freshwater plume arrived at this location. Consequent to the arrival of the fresh plume, the salinity fell by about 4 psu and the depth of the mixed layer decreased from about 30 m to 10 m. The mixed layer temperature remained in the range of 0.5°C. The surface circulation pattern that caused the fresh water plume to move to the location is explored using geostrophic currents calculated from the TOPEX/Poseidon data and Ekman flow from NCEP reanalysis winds. The cause was found to be Ekman flow. Two low pressure systems that formed in the northern Bay of Bengal appears to have played a crucial role by accelerating the offshore movement of the freshwater plume. After the arrival of the freshwater, the upper 30 m exhibits a 2-layer system. The top 15 m layer which moves southeastward is dominated by Ekman flow and a lower geostrophic layer with weak northward flow. The two layers are separated by the monsoon halocline that owes its formation to the arrival of the fresh water plume.

[22] **Acknowledgments.** Prof. G. S. Bhat kindly provided data on rainfall and surface fluxes and offered several suggestions. Thanks to Prof. Sulochana Gadgil for her encouragement to carry out this study and comments on the manuscript. Comments by two anonymous referees helped in improving the manuscript. Thanks are also due to Dr E. Desa and L. V. G. Rao of NIO, Goa (India) for their interest in BOBMEX studies. We are thankful to the participants of the ORV Sagar Kanya cruise 147A and the ship's crew for their help in the collection of data. India Meteorological Department provided Figure 12. The TOPEX/Poseidon data was downloaded from www.csr.utexas.edu. The 1-degree daily rainfall (1DD) data were provided by the NASA/Goddard Space Flight Center's Laboratory for Atmospheres, which develops and computes the 1DD as a contribution to the GEWEX-GPCP. BOBMEX observational experiment was supported by Department of Science and Technology, Department of Ocean Development, Defense Research and Development Organization and Department of Space.

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