

## Surface Circulation over the Shelf Off the East Coast of India during the Southwest Monsoon

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From the hydrographic data collected on board *R V Gaveshani* in the western Bay of Bengal during Aug.-Sept. 1978, fields of temperature, salinity and density have been constructed and the probable flow regime has been deduced. The studies indicate strong upwelling in the southern regions off the east coast of India. Vertical temperature and salinity structures north of Visakhapatnam show a predominant estuarine character and upwelling is not evident. In the northern regions, the flow is directed south and is consonant with that derived from wind stress curl distribution.

Hydrography of waters over continental shelf and adjoining areas of the Bay of Bengal undergoes distinct seasonal changes in response to the changing wind systems. In addition, large quantities of fresh water are discharged during the southwest monsoon at different locations all along the coast bordering the Bay of Bengal. These freshwater discharges influence the characteristics of these waters. While the general hydrographic features of the region have been studied<sup>1-9</sup>, the influence of fresh water discharges has not been studied in detail. There are relatively few studies on the oceanographic features of the Bay of Bengal during the southwest monsoon season. In the present communication, hydrography of waters in the western Bay of Bengal based on the data collected during Aug.-Sept. 1978 has been presented along with a study of the surface circulation and its relationship with the wind distribution.

### Materials and Methods

*R V Gaveshani* occupied 64 stations (Fig. 1) over the continental shelf off the east coast of India and adjoining offshore areas during 13 Aug. - 9 Sept. 1978. At all these stations, hydrographic and surface meteorological data were collected. Based on these, charts showing spatial variations of temperature, salinity and density ( $\sigma_t$ ) were prepared for surface and subsurface levels. Vertical distributions of temperature and salinity along 3 sections in the northern, central and southern regions were constructed (Fig. 1) to delineate the influence of freshwater discharges along the east coast of India. Observed wind field along with mean climatic wind pattern for August<sup>10</sup> and Sverdrup transport<sup>11</sup>, were also presented to study relationship between surface circulation and wind distribution.

### Results

*Spatial distributions*—Sea surface temperature

varies from 27° to 31°C in the study area (Fig. 1a). In the northern region it decreases from 30.5°C near the coast to 28.5°C offshore. In the southern regions alternate pockets of cold and warm waters are noticed in the inshore areas along the coast. The presence of warm and cold water zones develops frontal zones oriented in a near normal direction to the coast. Off Visakhapatnam, these features appear to be more prominent.

Surface salinity varies from 19.8 to  $33.8 \times 10^{-3}$  with low values occurring in the northern coastal regions around 20°N lat. and high values in the south (Fig. 1b). The warm waters in the inshore regions around 20°N coincide with the lowest salinities. The patterns of isohalines and isotherms appear to be similar. The horizontal salinity gradients offshore are strong in the northern regions.

Sigma-t at the surface (Fig. 1c) shows a large variation from about 10 to 19.5 in the nearshore regions and increasing offshore. In the southern region its variation is relatively small with values > 21.

*Vertical structures*—Distributions of temperature and salinity along section 1 in the northern region of the study area are given in Fig. 2a. The basic feature is the upsloping of the isotherms and isohalines offshore. The  $33 \times 10^{-3}$  isohaline as well as other isohalines indicate a strong halocline sloping upward reminiscent of a salt wedge in estuaries.

Fig. 2b on the other hand, shows a distinct variation in temperature and salinity structures in central region from the northern region. Both show dome like structures, seen more prominently at a depth of about 50 m, with near surface isohalines tending to become horizontal.

In the southern region (Fig. 2c), in contrast, the isohalines and the isotherms slope upwards towards the coast depicting intense upwelling characteristics. In

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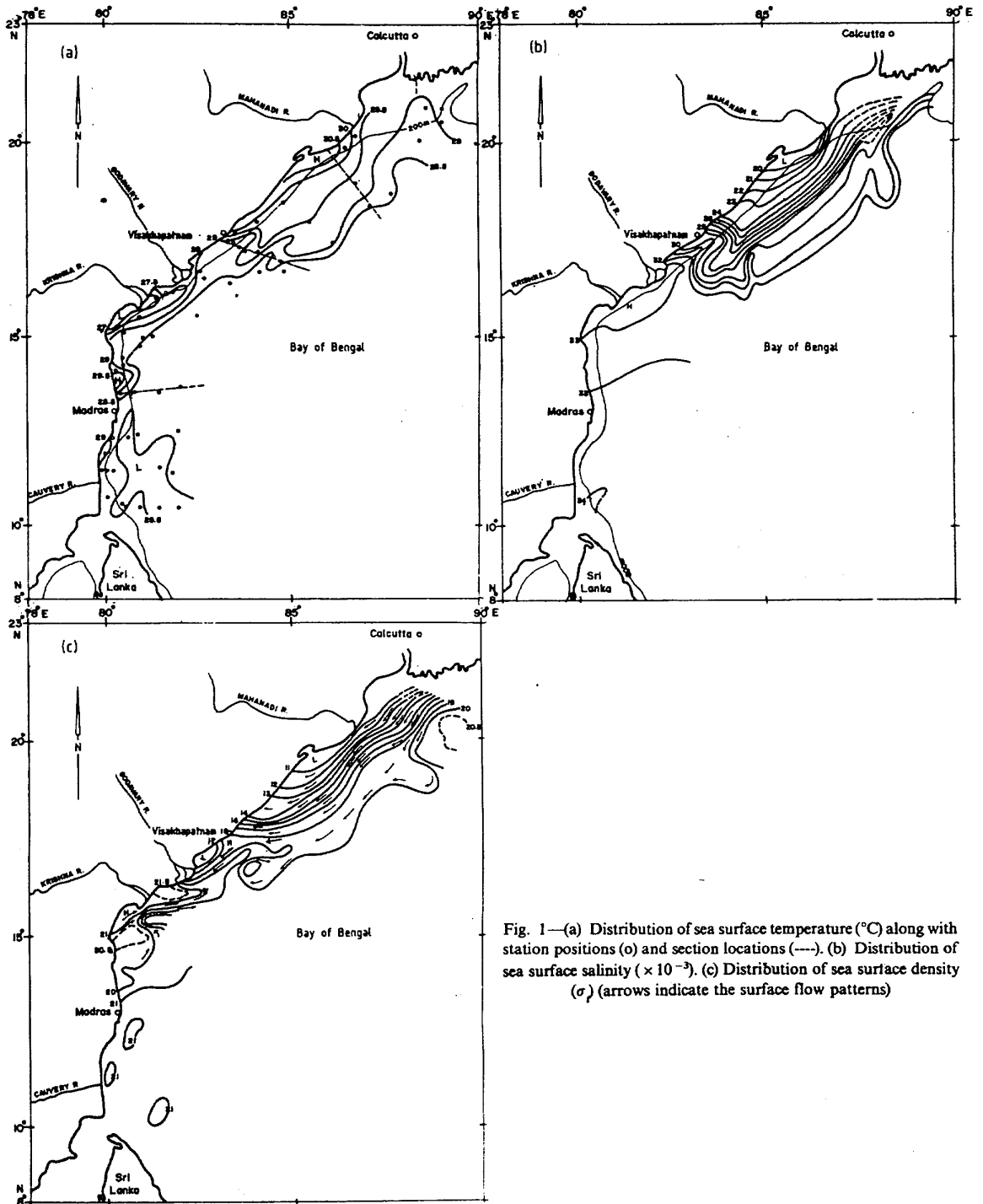


Fig. 1—(a) Distribution of sea surface temperature ( $^{\circ}\text{C}$ ) along with station positions (o) and section locations (---). (b) Distribution of sea surface salinity ( $\times 10^{-3}$ ). (c) Distribution of sea surface density ( $\sigma_t$ ) (arrows indicate the surface flow patterns)

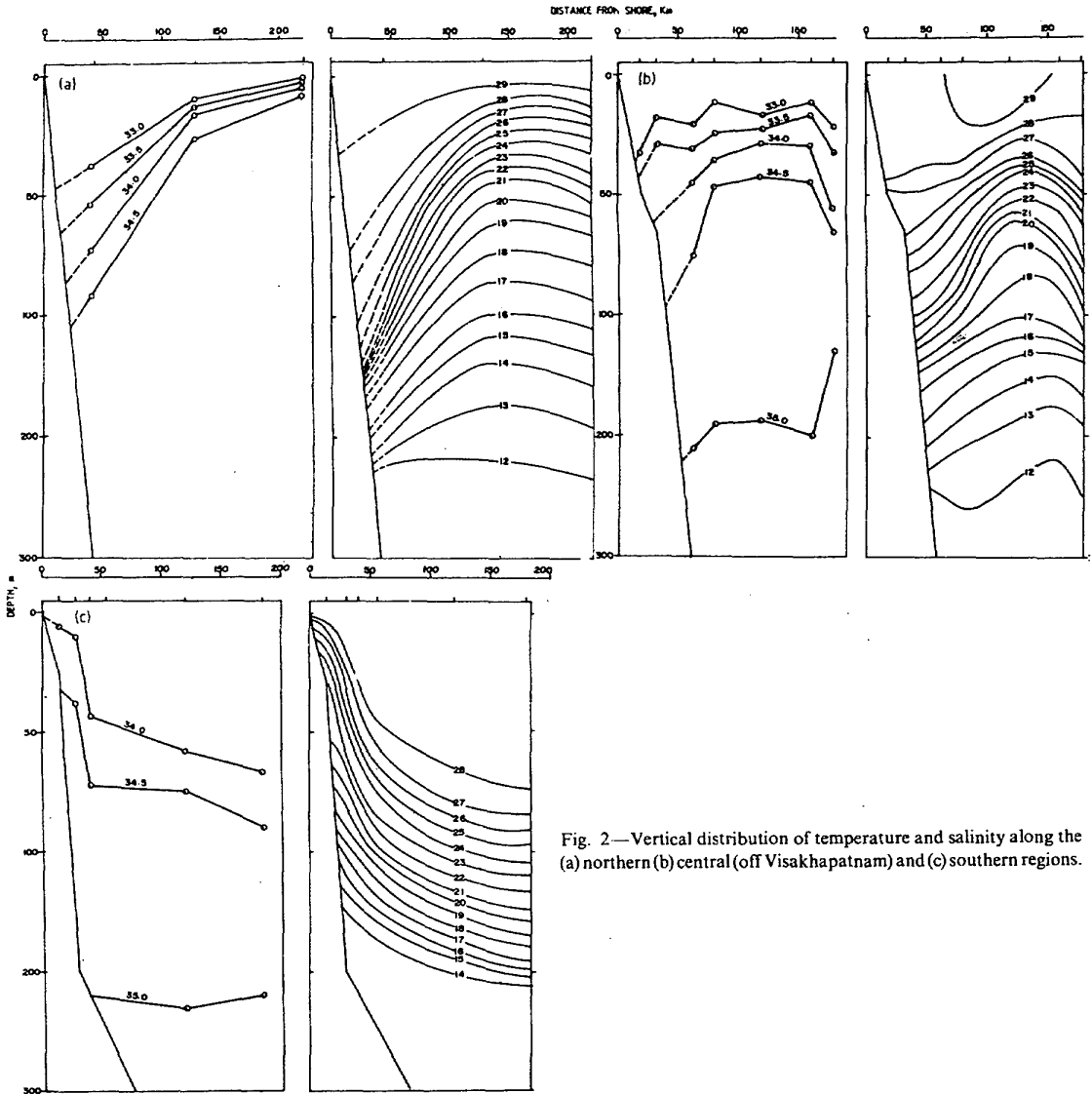


Fig. 2—Vertical distribution of temperature and salinity along the (a) northern (b) central (off Visakhapatnam) and (c) southern regions.

these regions, surface salinities are higher compared to those along the northern sections.

**Discussion**

Spatial distributions of temperature, salinity and density ( $\sigma_t$ ) show presence of a boundary separating the northern dilute waters from the southern relatively saline waters, situated around 17°N lat. Earlier studies<sup>1,2</sup> in this area during postmonsoon, northeast monsoon and hot weather seasons, based on the thermal and density fields also indicate the presence of such a barrier, which may shift its location with

seasons. This appears to be a permanent feature in the vicinity off Visakhapatnam.

Barring a few studies<sup>6</sup> on surface circulation, utilising the ship drift data, the flow field during the southwest monsoon (June-Sept.) season has not been studied. In order to gain a better understanding of the flow regime, the surface flow field has been deduced from the density distribution (arrows in Fig. 1c). Since the observations are conducted during a short period, it is believed that the flow field presented here can be representative of that during the southwest monsoon. It is clearly seen that north of Visakhapatnam

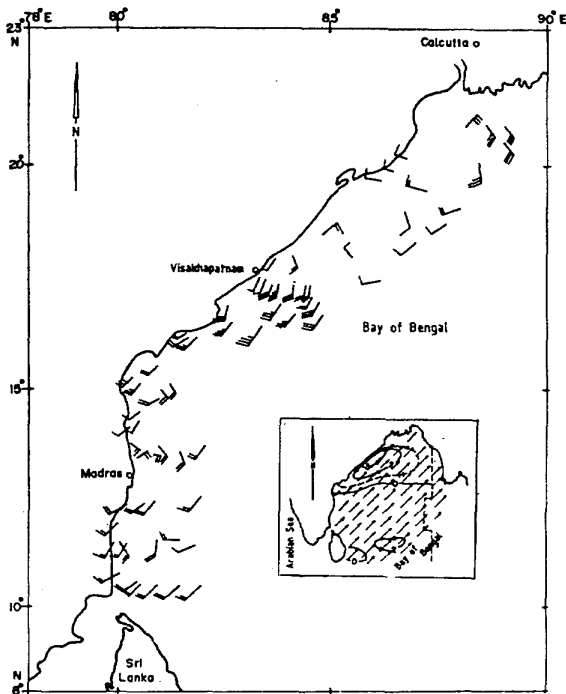


Fig. 3—Distribution of observed wind field in the inset map, arrows indicate mean climatic wind pattern and lines indicate Sverdrup transport based on mean windstress curl distribution for August (Shetye and Shenoi<sup>11</sup>).

adjoining the coast, a strong southerly flow exists all along the coast. South of Visakhapatnam, the southerly flow breaks up and no well defined field of motion is seen.

Fig.3 shows the observed winds in the period of survey, during which 2 monsoon depressions have crossed the study area<sup>12</sup>. In the regions uninfluenced by the weather disturbances, predominant southwesterlies are seen. In the areas coming under the influence of cyclones the wind field shows anomolous features from the mean monthly climatological feature shown in the inset map. Assuming that the surface circulation is wind-driven one would expect strong upwelling all along the east coast of India. During Aug. and Sept. The isohalines and isotherms slope upward (towards the coast in the southern region; Fig.2c) indicating upwelling. In the northern parts, the flow field is predominantly southwesterly, parallel to the coast and it does not assist upwelling. On the other hand, the

structures in Fig.2a give an impression that there could be sinking. The flow field coupled with the salinity distributions (Figs.1a-c and 2a) suggest that the southerly flow comprise freshwater discharged from Hugli and Mahanadi rivers.

Thus, it appears that the offshore mass transport which would have resulted due to Ekman drift in the coastal regions is compensated by freshwater flows as presumed by Rao and Sastry<sup>9</sup>. Since the surface waters are lighter, sinking if any, would not be intense associated with southerly flows and the upslope of isohalines offshore appears to be clearly an estuarine effect.

The full lines in inset map, Fig.3, show the mass transport based on the mean wind stress curl distribution for August<sup>11</sup>. The basic features are (1) a strong southwesterly transport along the east coast of India, (2) an eastward transport off Visakhapatnam, and (3) no identifiable transport in the southern region of the study area. Flowfield presented here though crude, depicts the same features and is in agreement with their studies.

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#### References

- 1 Rama Sastry A A & Balarama Murty C, *Proc Indian Acad Sci*, 46 (1957) 293.
- 2 Balarama Murty C & Rama Sastry A A, *Indian J Met Geophys*, 8 (1957) 1.
- 3 La Fond E C, *Andhra Univ Mem Oceanogr*, 1 (1954) 117.
- 4 Varadachari V V R, *On some meteorological and oceanographic studies of coastal waters off Waltair in relation to upwelling and sinking*, D Sc thesis, Andhra University, 1958.
- 5 La Fond E C, *Andhra Univ Mem Oceanogr*, 2 (1958) 1.
- 6 Varadachari V V R & Sharma G S, *J Indian Geophy Union*, 4 (1967) 61.
- 7 Rao L V G & Jayaraman R, *Proc Symp Indian Ocean*, 38 (1968) 184.
- 8 Rao D P, *A comparative study of some physical processes governing the potential productivity of the Bay of Bengal and Arabian Sea*, Ph D thesis, Andhra University, 1977.
- 9 Rao D P & Sastry J S, *Mahasagar*, *Bull Natn Inst Oceanogr*, 14 (1981) 1.
- 10 Hastenrath S & Lamb P J, *Climatic atlas of the Indian Ocean, Part 1 Surface climate and atmospheric circulation*, (Wisconsin, Univ Wisconsin Press) 1979, 10.
- 11 Shetye S R & Shenoi S S (Unpublished manuscript).
- 12 Srinivasan V, Ramakrishnan A R & Jambunadhan R, *Mausam*, 31 (1980) 495.