

Gyres in the NW Bay of Bengal — Some Observed Evidences

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Continuous observations of temperature, salinity and the flow at 4 stations off the rivers of Krishna, Godavari, Mahanadi and off New Moore Island, along the east coast of India, were made prior to the onset of the SW monsoon in 1982. The analysis showed that the flows off Krishna and Godavari were directed towards S-SW, whereas the flow off Mahanadi was towards N-NE and the flow off New Moore Island was completely dominated by the tide. Hydrography at these stations showed that the S-SW flows off Krishna and Godavari were associated with low temperature and high salinity waters and the N-NE flow off Mahanadi was associated with high temperature and low salinity waters. The available evidences suggest that these flows are associated with gyres, a clockwise gyre off Mahanadi and an anti-clockwise gyre off Krishna and Godavari with a probable frontal zone in between. The results also suggest that the tidal influence on the mean flow is appreciable only off New Moore Island.

Information on the circulation in the Bay of Bengal is based mainly on the climatological atlases (ship drift data), though a few attempts have been made to derive the flow field from temperature and density distributions and from satellite imageries. Along the coastal regions, information on currents help mainly in understanding the diffusion and dispersion characteristics of the waters around. In this investigation currents and hydrography have been studied off the rivers of Krishna, Godavari, Mahanadi and off New Moore island along the east coast of India, just before the onset of the SW monsoon in 1982. Though the length of the time series data at each station are rather short (one tidal cycle of 13 h) some of the features observed during this investigation are interesting and informative.

Materials and Methods

Observation points in the present study are located about 15-20 km off the coast (Fig. 1). The major rivers along this coast bring enormous amounts of fresh water mostly during the SW monsoon season. The tide in this area is of mixed semidiurnal type and during the observation period. The predicted maximum tide has been 76 and 86 cm off Krishna and Godavari respectively, 1.26 m off Mahanadi and 3.6 m off New Moore Island.

Out of the 2 tidal cycles in a day present observations coincided with the first maximum off Mahanadi and New Moore Island and with the second maximum off Krishna and Godavari. However, the differ-

ence between the first and the second maxima off Krishna and Godavari do not exceed 15 cm.

Continuous measurements of temperature, salinity, current speed and direction at 4 levels were carried out every 5 min interval for 13 h at each station using Aanderaa-RCM4 current meters suspended from the anchored vessel *R.V. Gaveshani* during June-July 1982. The current observations had to be confined to the sub surface layers (Table 1) because of the instrumental restrictions. Absence of rough seas during the observation provided minimum movements of the current meter array throughout.

Hourly vector averages were computed from 5 min current data and this hourly vectors were used in preparing the progressive vector diagram (PVD) at each station.

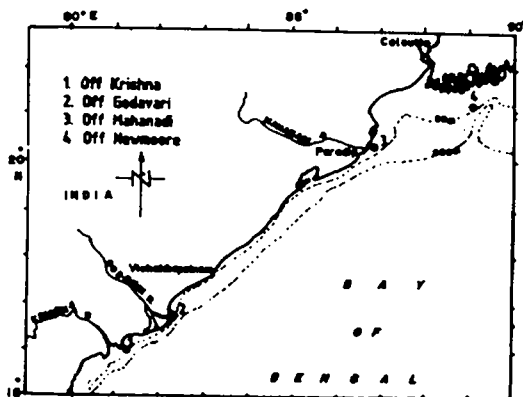


Fig. 1 — Station locations

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Table 1 — Details of Observations

Station off	Position		Depth (m)	Date & duration (hrs)	Sampling depths* (m)			
	lat. (N)	long. (E)						
Krishna	15°53'54"	81°17'00"	25	30.6.82-1.7.82 (1130-0005)	14.0,	16.7,	18.4,	20.1
Godavari	16°38'18"	82°23'54"	27	01.7.82-2.7.82 (1135-0120)	19.0,	21.7,	23.4,	25.1
Mahanadi	20°19'06"	86°57'36"	22	03.07.82 (0000-1410)	15.0,	17.2,	19.0,	20.5
New Moore Island	21°07'36"	89°03'18"	27	05.07.82 (0350-1720)	19.0,	21.7,	23.4,	25.1

*Parameters measured at each sampling depth: temperature, salinity, speed and direction.

Results

Flow Characteristics

Off Krishna — PVD for the station off Krishna during the 13 h period shows a mean flow towards SW which is almost parallel to the isobath (Fig. 2A). This figure also shows that during the first half of the observation the flow is dominated by the U-component and in relation to the tide this dominance occurs during the rising phase of the tide.

The observed variation in the U and V components of the flow (Fig. 3A) shows a weak tidal frequency. During the flood, while the U-component shows an increase the V-component has almost reduced to zero. However, during the ebb phase both U and V components have increased considerably. From this pattern it may be inferred that the mean flow at this station is towards SW and this flow is getting deflected towards the coast during the rising phase of the tide when the V-component is reduced very much. Similar behaviour of the flow is observed at the other levels also. Both U and V components have recorded a maximum flow speed of about 60 cm. sec⁻¹.

Off Godavari — The mean flow pattern off Godavari (Fig. 2B) is almost similar to that off Krishna except that the predominance of U-component observed off Krishna is not seen at this location. The U-component (Fig. 3A) which attains a maximum of about 20 cm. sec⁻¹ remains almost constant throughout, whereas the V-component with a maximum value of 50 cm. sec⁻¹ reduces to almost half of it during the rising phase of the tide. A corresponding rise in the U-component as seen in the case off Krishna is not observed here. Thus except for a decrease in the V-component the tidal influence at this location is not clearly identifiable. The flow remained unchanged with depth and exhibits very weak vertical shear.

Off Mahanadi — In contrast to the above 2 locations, the mean flow off Mahanadi shows a N-NE component (Fig. 2C). The rising phase of the tide induces a purely northward flow but during the falling

phase the flow has turned to east. U and V components (Fig. 3B) show that when there is a decrease in V and an increase in U during the flood at the previous 2 stations, a reverse trend is noticed at this location. At this station U and V components show maximum of 40 and 30 cm. sec⁻¹ respectively and the changes are not much with increase in depth.

Off New Moore Island — The flow at this location is completely dominated by the tide (Fig. 2D). The major axis of the ellipse is about 3 times the minor axis and shows a slight tilt towards the axis of the Hoogly river. The U and V components (Fig. 3B) show the tidal frequency very clearly. U and V-components record a maximum of about 60 and 40 cm. sec⁻¹ respectively.

The flow pattern presented above shows that the mean flows over a tidal cycle off Krishna and Godavari are towards S-SW and the flow off Mahanadi is towards N-NE. This feature points to the possible existence of a diverging or a frontal zone between the opposite flowing currents off Mahanadi and Godavari. Observations in between these 2 points are not available. However, as the water characteristics on either side of this anticipated front/diverging zone are likely to exhibit differences, the hydrography of the waters on both the sides is studied.

Hydrography of Waters

Temperature — In order to compare temperatures of the waters at these 4 stations the temperature time series at a common depth (19 m) are presented in Fig. 4A. The temperature at this depth does not show much variation with time off Godavari, Mahanadi and New Moore Island (average values 27°, 29.5° and 29°C respectively). On the other hand, temperature off Krishna shows very high fluctuations¹. However, the most important aspect emerging from Fig. 4A is that the waters off Mahanadi and Off New Moore are warmer than the waters off Krishna and Godavari by 2.5° to 3°C, which enable one to distinguish the area

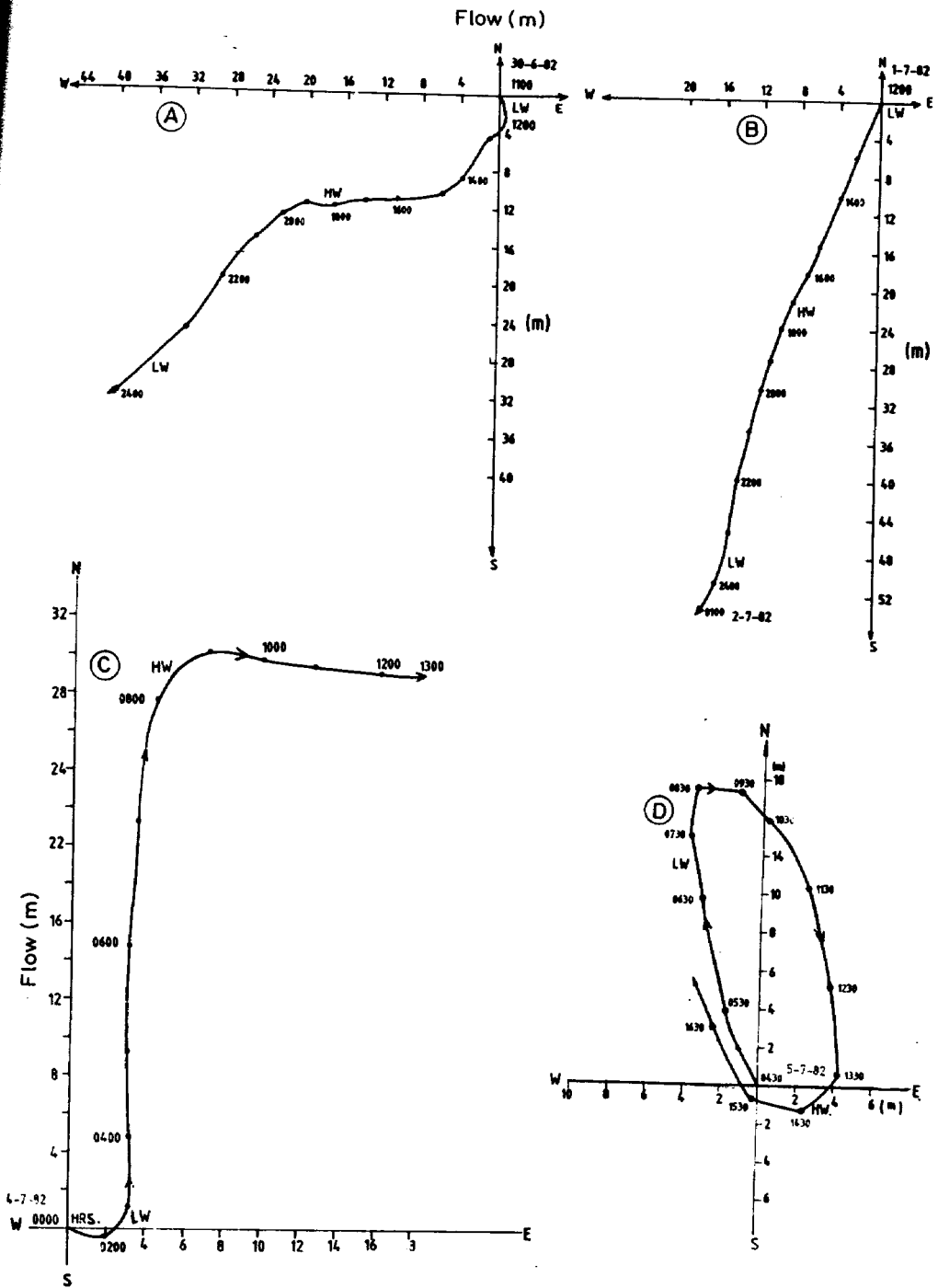


Fig. 2 — Progressive vector diagrams off (A) Krishna, (B) Godavari, (C) Mahanadi and (D) New Moore Island

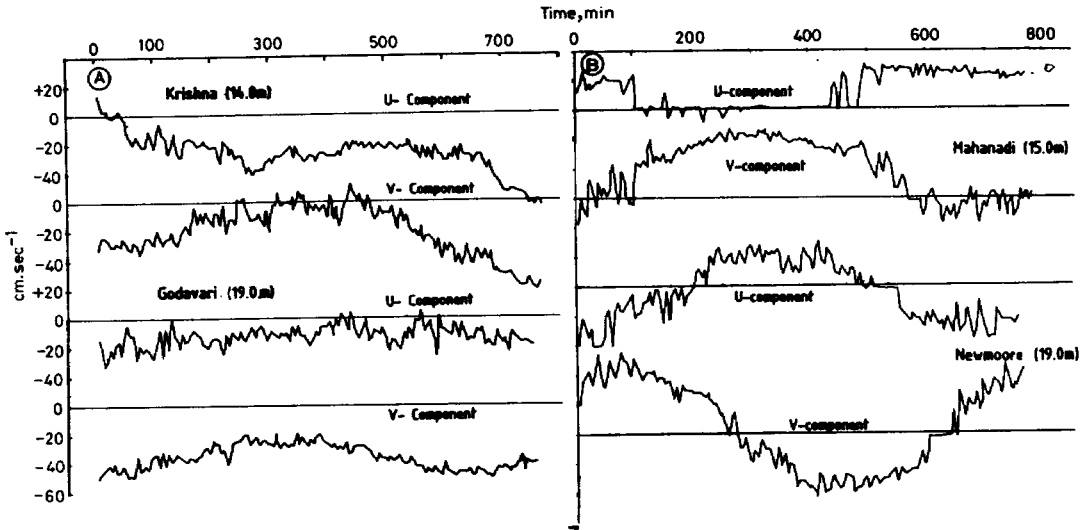


Fig. 3 — U and V components of flow (A) off Krishna and Godavari and (B), off Mahanadi and New Moore Island

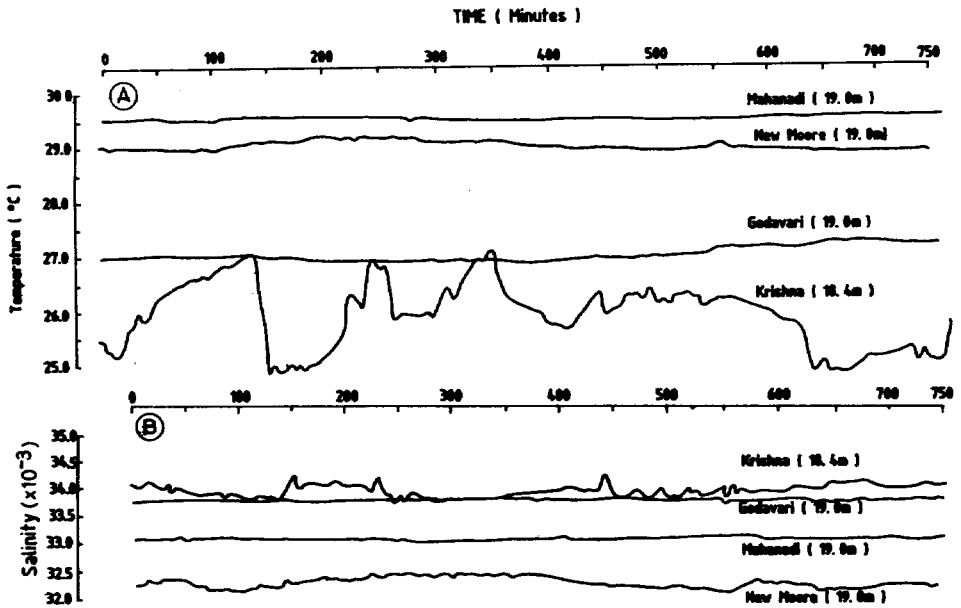


Fig. 4 — Temperature (A) and salinity (B) time series at all 4 stations

north of the anticipated front as warmer and south of it as colder.

Salinity — Fig. 4B presents the salinity time series at the same depth as that of the temperature at each station. Average value of 34×10^{-3} was recorded off Krishna and lowest (32.14×10^{-3}) off New Moore. Salinity values are almost constant off Godavari and Mahanadi where as slight variations are noticed off

Krishna and New Moore Island. An increasing tendency in salinity from north to south is also seen in Fig. 4. The difference between the average high and low salinities recorded is about 1.6×10^{-3} whereas the highest and the lowest values differ by 2.3×10^{-3} . It may also be seen that the salinity is lowest where the temperature is highest and vice versa.

Density — Similar to variations of salinity, comput-

ed density also shows an increasing trend from north to south. The average (time averaged for the column) σ_t values off Krishna, Godavari, Mahanadi and New Moore Island are found to decrease towards north in that order with values of 22.12, 21.88, 20.45 and 20.11 respectively. The difference between σ_t off Mahanadi and New Moore Island (northern area) is 0.34 and that between the Godavari and Krishna (southern part) is 0.24. However, the difference between σ_t off Godavari (southern) and Mahanadi (northern) is 1.43. In terms of density, it can be stated that high density water is present south of the anticipated front/diverging point and low density water north of it. Earlier we found that the waters off Mahanadi flow towards N-NE and those off Krishna and Godavari flow towards S-SW. Therefore we can relate the northward flow to low density water and southward flow to high density water.

Stability of Water Column

Static stability— Estimation of Brunt Vaisala frequency was made at all 4 stations using temperature and salinity data from the top and the bottom current meters employing the relation,

$$N^2 = -g/\bar{\rho} \frac{d\rho}{dz}$$

where, N — Brunt Vaisala frequency, g — acceleration due to gravity, $\bar{\rho}$ — average density, and z — depth below the sea surface. A large value for N implies high stratification/static stability and a small value indicates less stratification, and negative N shows turbulent overturning of water.

Fig. 5A shows the hourly means of every 5 min value of N^2 . The water column at all stations except off Godavari show variations in static stability with time. The maximum value for N is found off Krishna and minimum off Mahanadi. Though off Godavari the column of water sampled (which is very close to the bottom at all the stations) is more or less homogeneous, the fluctuations at other stations indicate that changes in vertical stability take place during such a short period of time even at this depth. Substantial drop in stability is noticed Off Mahanadi and New Moore Island during second half of the observation, i.e. during ebb tide. However, it is not possible to relate this drop to the tide directly because an increase in stability is noticed off Krishna during the same phase of the tide. One can only say that the water columns off Krishna and Godavari are statically more stable than those off Mahanadi and New Moore Island during the above period.

Dynamic stability— Vertical stability of water column also depends on the non-dimensional parameter—Richardson Number.

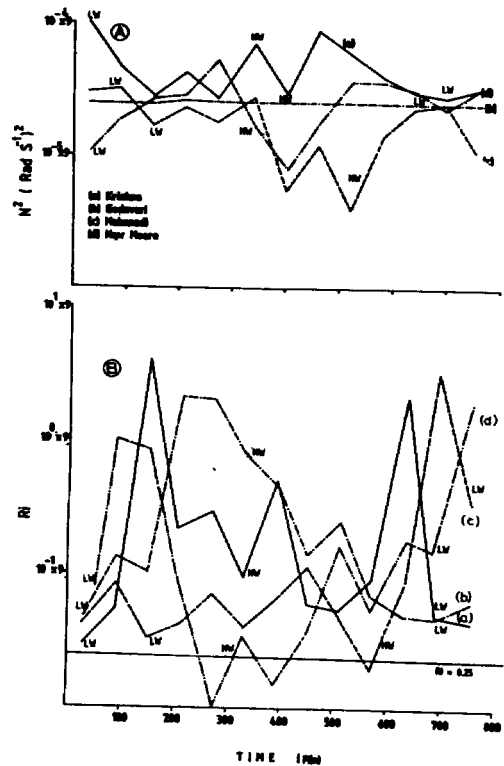


Fig. 5 — Hourly averages of (A) Brunt Vaisala frequency and (B) Richardson Number

$$Ri = N^2 / \left(\frac{\partial v}{\partial z} \right)^2$$

where the denominator represents the velocity shear. The water movement is vertically unstable and the fluid motion will be converted into turbulence² if $Ri < 0.25$.

Fig. 5B shows that the water columns off Mahanadi and New Moore Island are dynamically less stable than those off Krishna and Godavari. Though the Ri values off Krishna show a random variation, substantial drop in Ri is noticed off Godavari during the ebb when the flow is alongshore. In the case of Mahanadi and off New Moore Island, on the other hand, Ri has shown an increase during the same phase of the tide. As the shear has a major role in determining the value of Ri , the above features show that during ebb, the vertical shear is high off Godavari but is less off Mahanadi and New Moore Island. This difference in the behaviour of shear during the same phase of the tide could be that in the case off Mahanadi the flooding tide contributed towards an increase in the mean flow and a decrease (towards S-SW) off Godavari. Thus

the possibility of less shear and hence less dynamic instability exists during the flood off Mahanadi and New Moore but during ebb off Krishna and Godavari.

Discussion

The results show that the mean flows, over a tidal cycle, off Godavari and Krishna are directed towards S-SW and flow off Mahanadi is towards N-NE (Fig. 2). This suggests the presence of a diverging point or a frontal zone between Godavari and Mahanadi. The presence of warm and less dense water off Mahanadi as compared to the waters off Godavari and Krishna (Fig. 4) lends support to the above suggestion. The cold water expected of a diverging point along the coast would have advected towards either sides. This should have been recorded atleast off Mahanadi and Godavari if only advection of the cold waters is present. However, the present observation shows that cold water is present only off Godavari, and not off Mahanadi. Moreover, the flow resulting from the observed density gradient would have been something different from the observed pattern. Therefore it is speculated that the observed differences in the water characteristics at these 2 locations are associated with gyres — a clockwise gyre with warm and less dense waters off Mahanadi and an anti-clockwise gyre with cold and dense waters off Godavari and Krishna. While admitting to some extent that the present data are not sufficient to arrive at this conclusion, a review of some of the earlier studies³⁻⁷ show that eddies are almost a permanent feature in this area. The flow derived from temperature and density fields³⁻⁵ identify rotatory motion almost in the same region. From the analysis of the historical data⁶ an anti-clockwise gyre has been identified at the head of the Bay (between 17° and 22°N) with a confluence at 16°N and 88°E. While processing the satellite imageries during Sept 1972, Krishna Rao⁷ has located an anti-clockwise gyre near the head of the bay, and a clockwise gyre between 15° and 17°N with a confluence in between 17° and 18°N. The flow derived by Krishna Rao⁷ corroborates the results obtained in the present study except that the directions of both the cells are reversed. This discrepancy in the direction of rotation of the gyres could be attributed to the fact that these results pertain to 2 different seasons—one during (or after) the monsoon and

the other before the monsoon. If that is the case then we may arrive at the conclusion that the gyres identified in N-W Bay of Bengal reverse their directions with the change in season, similar to those observed in the Arabian Sea⁸. However, more precise observations are needed to confirm this.

Computations show that the warm water region is statically and dynamically more unstable than the cold water region, and it is yet to be confirmed whether this result is in conformity with observations made in the eddy regions in the other parts of the world oceans.

The results of the present study also show the extent of the influence of tide on the circulation in this region. It is found that the mean flows are least affected by the tides off Krishna, Godavari and Mahanadi probably due to the low values of the tide at these locations. However, off New Moore Island, where the tidal value is high the flow is completely dominated by the tide.

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