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Observed variability in the current field during summer monsoon experiments — Part I : Northern Bay of Bengal

R. R. RAO, K.V. SANIL KUMAR and BASIL MATHEW

Naval Physical and Oceanographic Laboratory, Cochin

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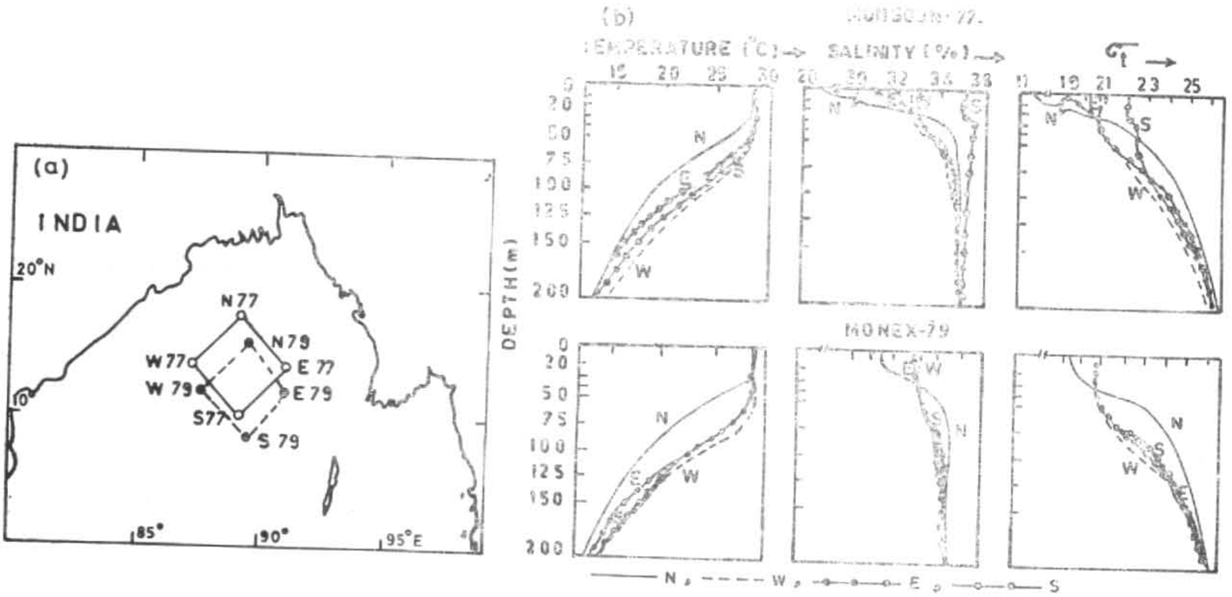
सार — मानसून-77 और मौनेक्स-79 क्षेत्र प्रयोगों के दौरान सोवियत रुस स्थिर पोत बहुभुजों में प्रसारित लंगर रेखाओं से प्राप्त धारा मीटर अभिलेखों के उपलब्ध समय श्रृंखला आंकड़ा सेटों का प्रयोग करते हुए उत्तरी बंगाल की खाड़ी के ऊपरी स्तरों के धारा क्षेत्र में प्रेक्षित अल्पावधि परिवर्तनशीलता का परीक्षण किया गया। ऊपरी 200 मी जल स्तम्भ में क्षैतिज वेग की प्रेक्षित परिवर्तनशीलता और संरचना की व्याख्या करने के लिए सतही पवनों के अतिरिक्त तापमान और लवणता के उर्ध्वाधर प्रोफाइलों पर संपूरक समय श्रृंखला आंकड़ा सेटों का भी प्रयोग किया गया। यद्यपि प्रेक्षण व्यूहों में तापीय प्रवृत्ति सजातीय प्रतीत होती है पर लवणता और धारा प्रवृत्तियों में काफी अंतर पाये गये हैं। प्रबल उर्ध्वाधर स्तरण जोकि उत्तरी बंगाल की खाड़ी में परिवर्ती होता है प्रेक्षित ऊपरी महासागरीय प्रवाह प्रवृत्ति को प्रभावित करता है एकमैन प्रकार के संतुलन के लिए सुस्पष्टता, बैरोक्लिनिक और नदी चालित परिसंचरण विधियों की महत्ता को इंगति करता हुआ कुछ कमजोर था। परिसंचरण का दक्षिणावर्त भंवर रुप केवल मौनेक्स-79 के दौरान स्पष्ट था न कि मानसून-77 में। धारा मीटर अभिलेखों की वेक्टर समय श्रृंखलायें मानावलीय विश्लेषण के अनुसार थी। जिसका प्रयोग उग्र दोलनों की आवर्तिताओं को पहचानने और परिसंचरण की प्रकृति का अनुमान लगाने के लिए किया जाता है। मौनेक्स-79 के दौरान प्रवाह प्रवृत्ति में तीन से पांच दिन के दोलन पाए गए।

ABSTRACT. The observed short term variability in the current field of the upper layers of the northern Bay of Bengal is examined utilising the available time series data sets of current meter records obtained from mooring lines deployed from USSR stationary ship polygons during MONSOON-77 and MONEX-79 field experiments. Supplementary time series data sets on the vertical profiles of temperature and salinity in addition to surface winds were also made use of to describe the observed variability and structure of the horizontal velocity in the upper 200 m water column. Although the thermal regime appeared to be homogeneous within both the observational arrays, considerable differences were noticed in the salinity and current regimes. The strong vertical stratification which is variable in the northern Bay of Bengal appeared to have influenced the observed upper oceanic flow regime. Evidence for Ekman type of balance was rather weak suggesting the importance of baroclinic and river driven circulation modes. A clockwise eddy type of circulation was evident only during MONEX-79 but not during MONSOON-77. The vector time series of current meter records were subjected to rotary spectral analysis to identity the periodicities of energetic oscillations and to infer the nature of circulation. Three to five-day oscillations in the flow regime were noticed during MONEX-79.

1. Introduction

The seasonal reversing monsoons are known to influence the annual cycle of the near surface circulation patterns of the northern Indian Ocean. Virtually all the information on the structure of the upper ocean flow field in this area was derived mostly from (*i*) monthly mean currents based on observations of ship drifts (KNMI 1952, U. S. Navy 1976, Cutler and and Swallow 1984), (*ii*) charts of dynamic topography (Varadachari *et al.* 1968, Duing 1970, Wyrtki 1971), (*iii*) physical properties (Gopalakrishna and Sastry 1986), (*iv*) satellite imageries (Rao 1974, Legeckis 1987) and (*v*) drift buoy trajectories monitored by satellites (Molinari *et al.* 1990). The clockwise gyral circulation in the northern Indian Ocean during summer monsoon and its reversal during winter monsoon (KNMI 1952, Wyrtki 1971), the appearance of the equatorial jet during both the monsoon transitions (Wyrtki 1973, Reverdin *et al.* 1983), the appearance of the equatorial undercurrent during the first half of the year (Knox 1976, Leetma and Stommel 1980) were broadly identified from these studies. The life cycle of the Somali current and the associated eddy field was probed in greater detail (Leetma *et al.* 1982, Swallow *et al.* 1983, Schott 1983) compared to other important current systems. A few measurements were made to describe the equatorial jet and undercurrent at specific longitudes (Taft and Knauss 1967, Knox 1976, Luyten and Swallow 1976, Leetma and Stommel 1980). Practically no direct current measurements were made in the central and eastern Arabian Sea and the Bay of Bengal prior to the conduct of summer monsoon field experiments. For the first time USSR ships laid current meter moorings in the central Arabian Sea (MONSOON-77), northern equatorial Arabian Sea (MONEX-79) and northern Bay of Bengal (MONSOON-77



Figs. 1 (a & b). (a) Station location map and (b) Mean vertical profiles of temperature, salinity and at all the locations during M-77 and M-79

and MONEX-79) during the summer monsoon seasons of 1977 and 1979. Using some of these data sets Gopalakrishna *et al.* (1988) described the relationship between daily averaged surface winds and sub-surface currents. However no studies have been reported giving a detailed description of the observed circulation regime and its spectral decomposition.

One of the major scientific objectives of the summer monsoon experiments was to probe the role of Bay of Bengal on the genesis of monsoon depressions/storms. Accordingly USSR deployed four ship stationary polygons in the northern Bay of Bengal during MONSOON-77 and MONEX-79 field experiments. In addition to atmospheric measurements from these research ships, the hydrographic properties and currents in the upper layers of the sea were monitored to gain an insight into the physical processes associated with the genesis of a depression/storm over the Bay of Bengal. A few diagnostic studies were carried out earlier utilising these data sets to describe the short term variability in the observed temperature and salinity fields (Rao *et al.* 1991, Rao and Mathew 1988, Rao and Sanil Kumar 1991) and the genesis of meteorological disturbances (Rao and Rao 1986, Rao *et al.* 1987). Utilising the current meter records collected during MONSOON-77 and MONEX-79 experiments, the observed features of near surface flow field for the northern Bay of Bengal are presented in this paper.

2. Data and methodology

USSR deployed four ship stationary polygons over the northern Bay of Bengal during MONSOON-77 and MONEX-79 (designated as M-77 and M-79 respectively in the following discussion) field observational programmes, Fig. 1 (a). Current meter data were collected at 25, 50, 100, 150 and 200 m depths at half hourly intervals for durations of the order of 1-2 weeks. These data were reported at a resolution of 1° in direction and 1 cm/s in speed (accuracy in direction ± 10° and in speed ± 2 cm/s). The corresponding surface wind data at 10 m height were also collected at one hourly intervals. The bathythermograph and Nansen casts made at 3-6 hourly intervals were utilised to construct mean profiles of temperature and stability (Brunt-Vaisala frequency) regimes at all locations. In the following discussion the stations at northern, eastern, southern and western corners of the polygon are designated as N, E, S and W respectively.

The observed current records usually exhibit oscillations of different periodicities. The rotary spectral method is more appropriate in determining spectral energy estimates of time series of vector current measurements compared to the Fourier analysis of scalar zonal and meridional components (Gonella 1972). The rotary spectral estimation is based on the decomposition of velocity field $V = u + iv$. The Fourier transform for the vector time series is

$$V_n = \frac{1}{d} \int_0^d V(t)\, e^{-i\omega t}\, dt$$

where u and v denote the zonal and meridional components. The current meter records were low pass filtered (Bloomfield 1976) with a cut off frequency at 0.08 cph (12.5 hr) to remove frequencies greater than that of semidiurnal tide and the filtered data are subjected to rotary spectral analysis.

3. Results and discussion

3. 1. *Observed mean hydrography*

The behaviour of the monsoon in the present study years was contrasting. During 1977, the monsoon behaviour was above normal (Anon. 1978) while in

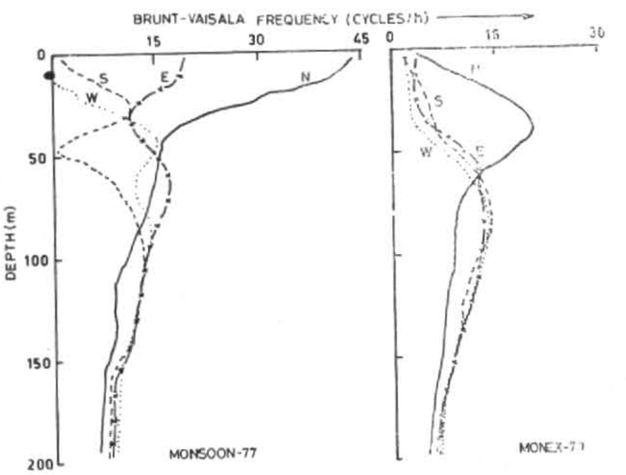


Fig. 2. Mean vertical profiles of Brunt-Vaisala frequency at all the locations during M-77 and M-79

1979 it was below normal (Awade *et al.* 1986). The freshwater inputs through rainfall and river discharges into the Bay are expected to differ during the monsoon seasons of both the years. Added to these differences, the observations during M-79 were collected one month earlier to those of M-77. The approximate physical separation between respective corners (*i.e.*, between the northern locations of both the stationary polygons of M-77 and M-79 etc) was of the order of about 60 nm.

The mean distributions (corresponding to the observational period) of the vertical profiles of observed temperature, salinity and derived σ_t (density) for the polygons of M-77 and M-79 are shown in Fig. 1(b). During both M-77 and M-79, the mean temperature profiles at N are characterised by a shallow mixed layer with steep thermocline below. The mean temperature profiles at the other three locations showed a relatively deeper mixed layer with weaker underlying thermocline. Relatively larger differences are noticed in the corresponding salinity profiles at the nothern and the other locations. During M-77 the salinity differences were relatively larger in the upper layer ($\sim$30 m) within the polygon compared to those of M-79. During M-77 massive river discharges as mentioned earlier probably produced lowest surface salinities (<22‰) at N location producing a strong halocline below the surface. All the other locations showed relatively higher salinities with isohaline layers extending from surface to about 20 to 30 m depth. These spatial differences in the vertical salinity distribution within the polygon are mainly attributed to the proximity of the station to the river mouth and local meso-scale circulation patterns causing differential advection of salinity. In the northern Bay of Bengal a clockwise circulation (US Navy 1976) is probably driven by balancing effects between local wind stress, geopotential field and massive river discharges. Although the relative importance of these various driving mechanisms is not clear at present due to inadequate simultaneous measurements of surface winds, sub-surface currents, geopotential field and river discharges. One cannot, perhaps, undermine the contribution of massive river discharge which produce large horizontal variability in the near surface salinity field. Sarma *et al.* (1988) have shown large spatial variability in the observed salinity field at the head Bay during M-77 and M-79. The influence of these river discharges is clearly noticed in the salinity field mostly limiting to the topmost 30-50 m water column (Levitus 1982). During M-79, salinity was not only higher than that noticed during M-77 at the polygon corners but also the spatial differences within the array were weaker. In addition during M-79 comparatively a weaker halocline was noticed in the depth range of 10-50 m at N location and isohaline layer was noticed in the top 50 m water column at the other three locations. During both the experiments the salinity profiles below 50 m depth resembled each other with diminishing spatial differences.

Brunt-Vaisala frequency (BVF) was calculated utilising the mean temperature and salinities for each observational period for all the locations (Fig. 2). Relatively large values of BVF are noticed during M-77 at N and E locations in the near surface layer due to the development of strong halocline caused by freshwater discharges from the rivers *Ganges* and *Brahmaputra* at the head Bay. The observed spatial variability of BVF was also large during M-77 in the upper layers within the observational array. The variability of BVF practically became insignificant with depth below 100 m. During M-77, the large values of BVF and a sharp decrease in the topmost 50 m water column is prominently seen only at N location (closest station to the river mouth). In the near surface layers the BVF values decreased in a clockwise manner suggesting the reduction of dilution from N to W locations. However, the situation during M-79 was more or less similar to that of open ocean conditions with the only exception at N location due to its proximity to the river mouth as inferred from low salinity values there.

3.2. *Short term variability in the current field*

Direct measurements of currents at half hourly intervals were utilised to describe the short term variability in the flow regime at selected depths in the top 200 m water column. These data provide a good description of the vertical structure of velocity field in the upper 200 m water column. The current meter data were filtered to remove the variance with periods less than semidiurnal (M2) tide, *i.e.*, 12.5hrs (0.08 cph). The smoothed data are shown as sticks for all the 4 locations in Figs. 3 & 4 for M-77 and M-79 respectively. The observed surface wind data were also subjected to similar processing and the wind sticks are shown in the topmost panels of Figs. 3 and 4. During M-77, the surface winds were predominantly from southwest at all locations with an average speed of 9m/s implying a near steady wind forcing over the observational array (Fig. 3). However, the sub-surface current filed showed some interesting variations in space and time. The overall flow was towards southeast at N and S locations, and towards northwest at E and W locations suggesting convergence in the northeastern sector and divergence in the southwestern sector. The flow weakened very rapidly with depth only at N and E locations while the weakening was moderate at S and W locations. This rapid downward decay of current strength only at N and E locations may be attributed to weak downward transport of wind stress due to strong stratification in the pycnocline.

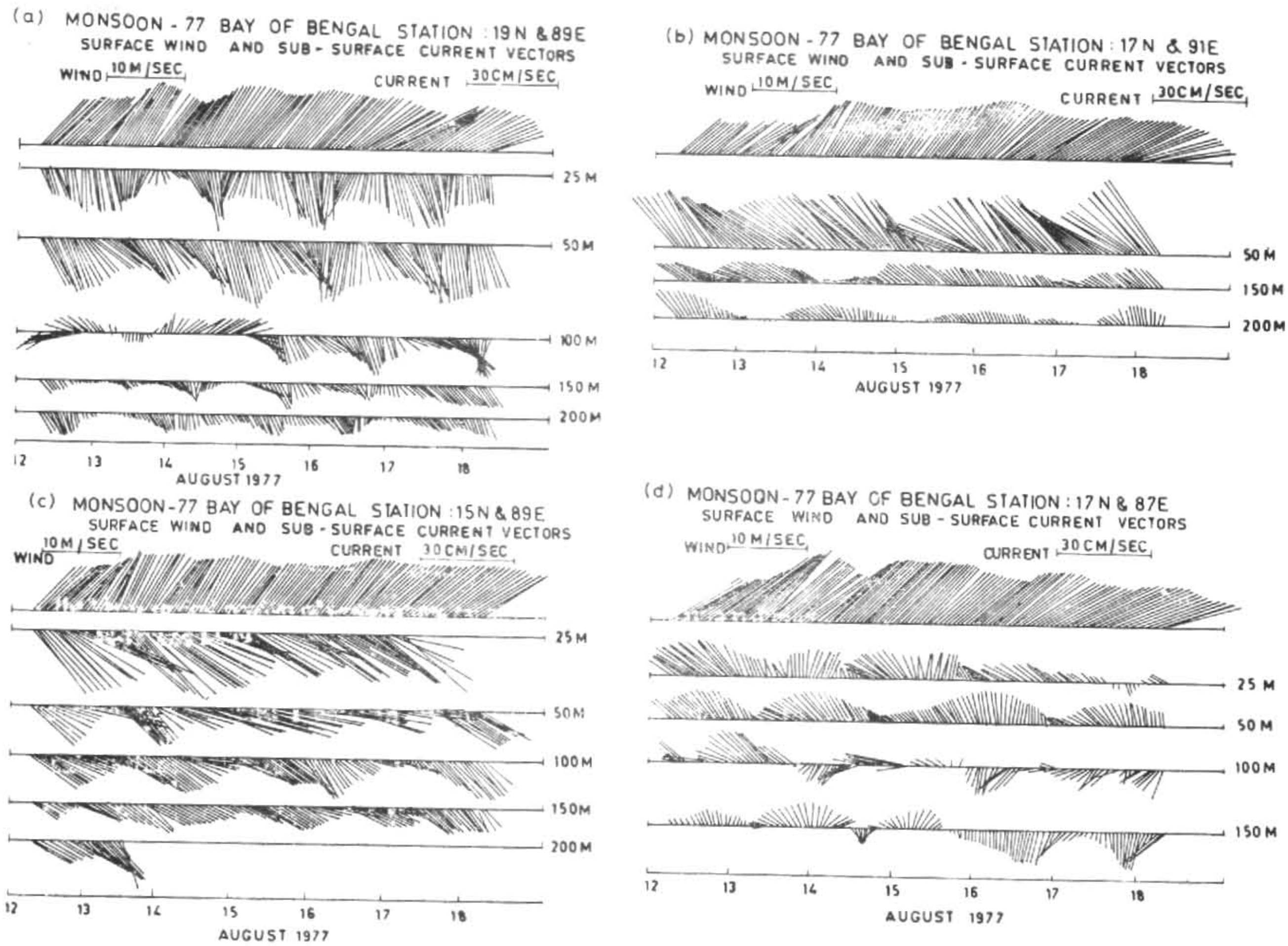


Fig. 3. Surface wind and subsurface current vectors at all the four locations during M-77

During M-79 the surface winds were also from southwest at all locations with an average speed of 7m/s (Fig. 4). The flow at N and W was towards northeast while at E and S locations it was towards southwest. A close examination of the current sticks indicates the presence of a clockwise eddy type of circulation extending from 25 m to 200 m depth. From the temperature field at this area Swallow (1983) inferred a weak clockwise eddy 400-500 km across, centred near S location where the 20°C isotherm was depressed by 30 m. The reduction in the current speed with depth at N and E locations is not comparable in magnitude to that noticed during M-77. This feature perhaps, clearly demonstrates the importance of local stratification in the downward transport of wind stress. Flow was strong and steady throughout the 200 m water column only at the S location.

During both the experiments the flow regime exhibited a well defined energetic oscillatory nature. These synoptic scale fluctuations show an excellent correspondence with the local inertial periods. Pollard and Millard (1970) successfully demonstrated the importance of local wind forcing on the amplitude of inertial oscillations beneath the mixed layer. The amplitude of these inertial oscillations also appeared to be related to the local stratification.

3.3. *Mean wind and current pattern*

The surface wind and sub-surface current data were vectorially averaged for the total observational period and the mean vectors for M-77 and M-79 are presented in Fig. 5. During both M-77 and M-79 the surface winds were predominantly from southwest with average speeds of 9 m/s and 7m/s respectively. But the observed current vectors during both the experiments do not resemble each other. A well defined clockwise circulation is evident only during M-79 when the flow did not show any significant variation either in direction or in speed with depth. Apparently no Ekman type of balance is noticed during either of the experiments with the only exception at S location during M-77. The forcings produced by thermohaline gradients and massive river discharges might have been significant in producing the observed flow patterns in the upper 200 m water column.

The significant weakening of the flow from the mixed layer to thermocline noticed at N and E locations during M-77 was not noticed during M-79 when the pycnocline at N and E locations was relatively weaker. On the other hand, during M-79 the flow was consistently stronger throughout the 200 m water column at all the four locations. This feature suggests the importance

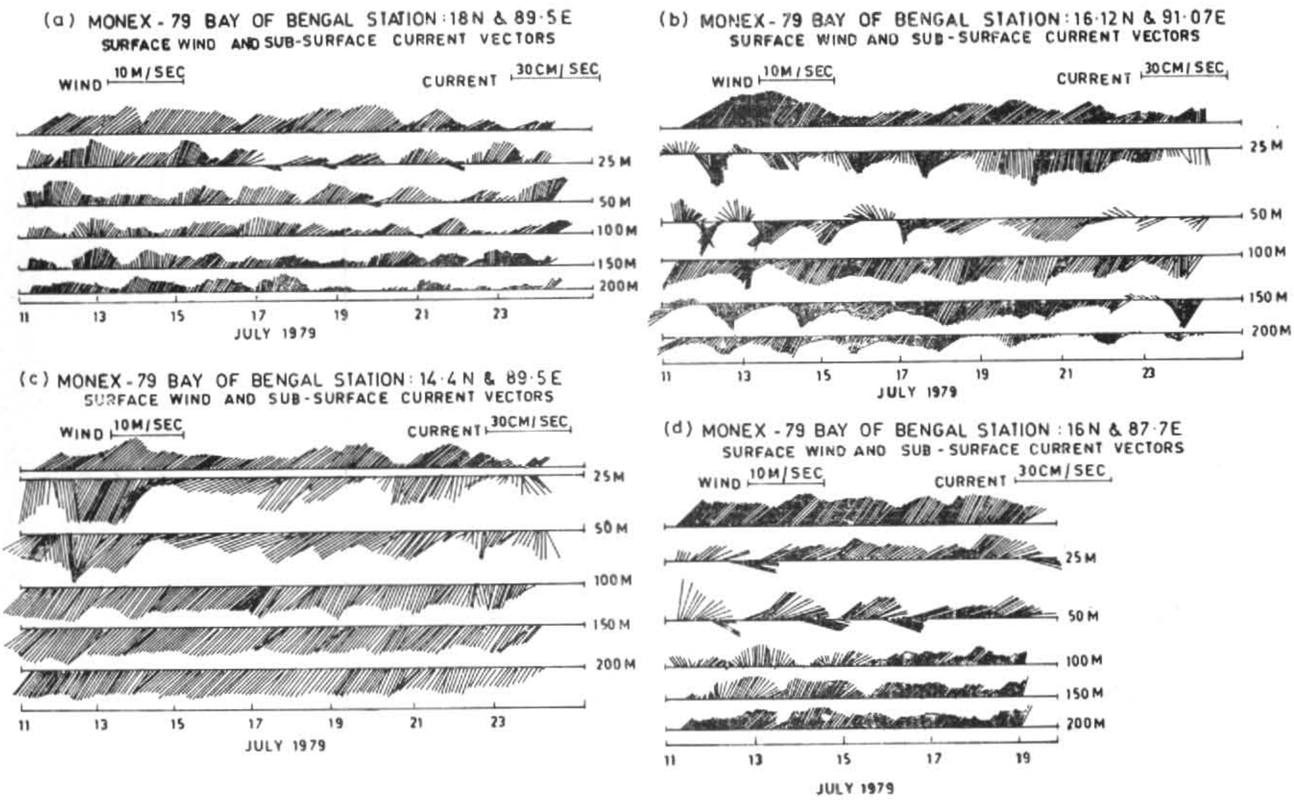


Fig. 4. Surface wind and subsurface current vectors at all the four locations during M-79

TABLE 1

	N				E				S				W			
	u	σ_u	v	σ_v	u	σ_u	v	σ_v	u	σ_u	v	σ_v	u	σ_u	v	σ_v
MONSOON-77																
Wind (m/s) at 10m ht	7	2	6	2	6	2	5	2	6	2	7	1	8	2	6	2
Current (cm/s) at 25m	3	22	—22	19					43	22	—26	32	—8	10	8	17
,, ,, 50m	12	21	27	18	—31	18	27	20	38	18	—12	25	—8	10	10	11
,, ,, 100m	5	22	—7	20					24	13	—14	16	—12	21	—2	24
,, ,, 150m	7	12	—7	11	—12	10	7	10	20	10	—11	11	—3	13	—3	16
,, ,, 200m	5	10	—8	10	—5	8	5	8	28	10	—16	12				
MONEX-79																
Wind (m/s) at 10m ht	5	3	5	2	6	2	4	3	5	3	4	3	5	2	4	3
Current (cm/s) at 25m	29	22	11	26	—25	29	—28	29	—3	27	—19	27	16	19	11	23
,, ,, 50m	31	21	7	30	—30	24	—26	14	—21	26	—12	29	14	16	11	18
,, ,, 100m	10	17	10	17	—22	14	—31	12	—16	17	—24	14	12	14	10	15
,, ,, 150m	13	13	13	14	—31	13	—32	12	—13	16	—16	16	10	12	11	13
,, ,, 200m	14	9	15	10	—22	12	—29	9	—9	14	—10	14	8	10	9	11

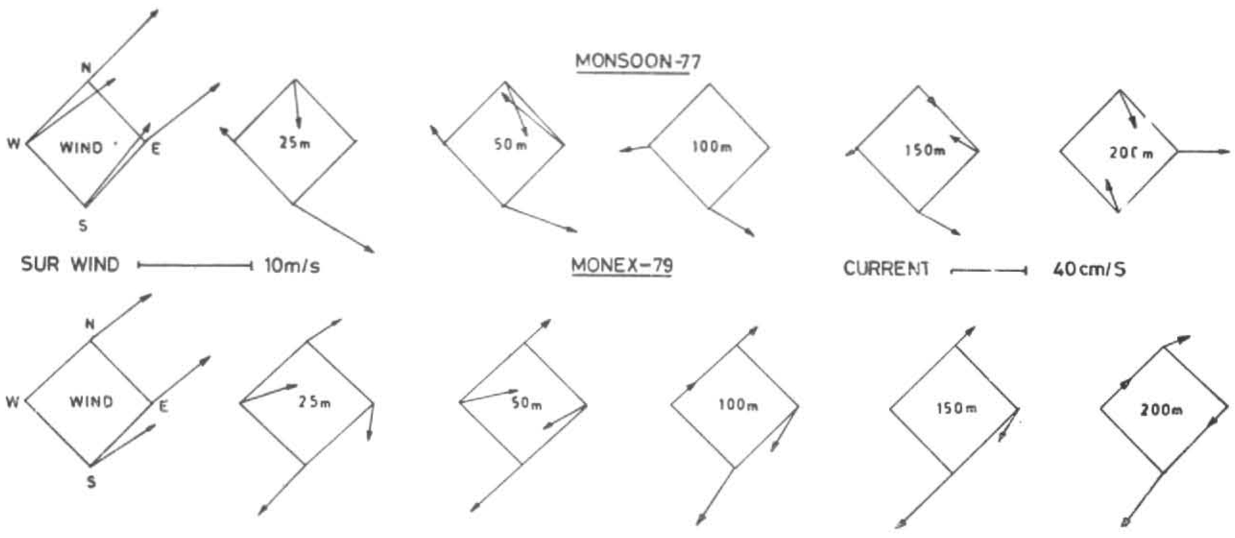


Fig. 5. Mean surface wind and subsurface current vectors at all the four locations during M-77 and M-79

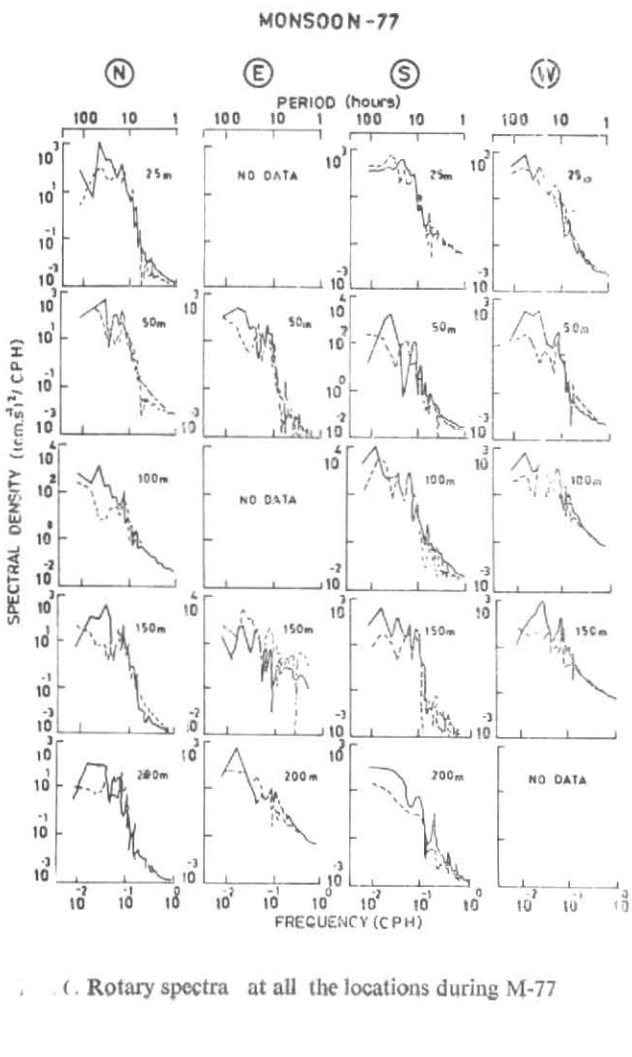


Fig. 6. Rotary spectra at all the locations during M-77

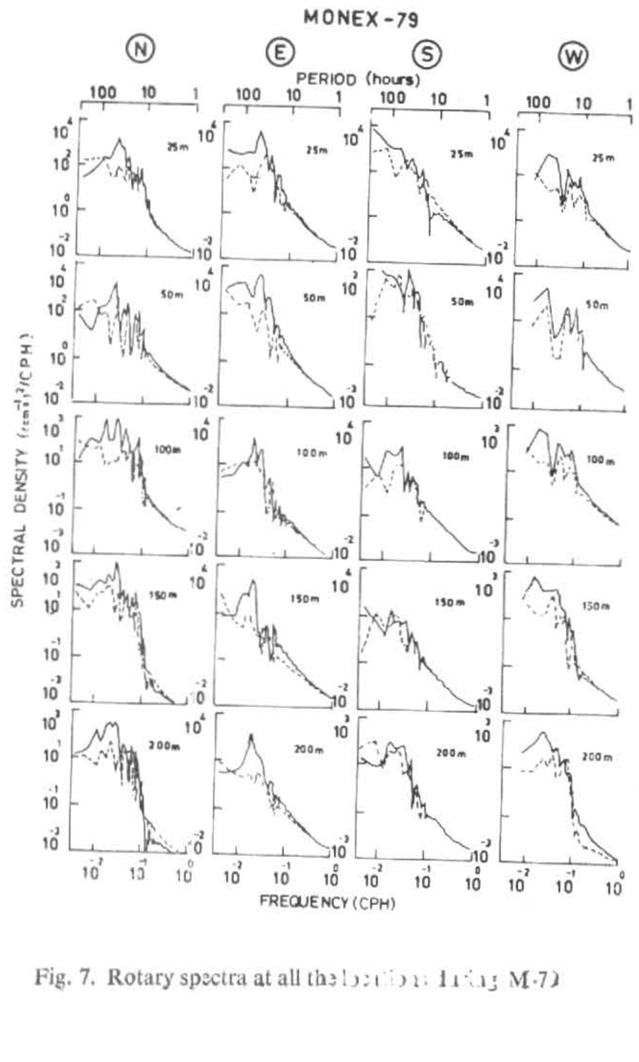


Fig. 7. Rotary spectra at all the locations during M-79

of the strength of pycnocline in determining the vertical structure of the flow in the mixed layer and thermocline. The clockwise eddy type of circulation can also be inferred from the mean flow field only during M-79. The stronger flow regime noticed at S location also suggests that the centre of the clockwise eddy was located towards south within the observational array which is in accordance with an earlier inference of Swallow (1983). This eddy type of circulation is noticed throughout the 200 m water column. The mean and standard deviation values of zonal and meridional components of currents and surface winds at all the locations and depths for M-77 and M-79 are shown in Table 1.

3.4. *Rotary spectra*

Rotary spectra were computed to examine the distribution of velocity variability over a range of frequencies both positive, corresponding to velocity vectors that rotate anticlockwise with time, and negative, corresponding to velocity vectors that rotate clockwise with time. These clockwise (continuous line) and anticlockwise (dashed line) spectral estimates for all the locations and depths for M-77 and M-79 are presented in Figs. 6 and 7 respectively. The most striking feature of the rotary spectra is the dominance of the clockwise component over anticlockwise component during both M-77 and M-79, especially in the low frequency band. In general, the spectral energy is about an order of magnitude higher in the clockwise spectra compared to the anticlockwise spectra. The peaks in the clockwise spectra mostly correspond to inertial, diurnal and semi-diurnal periodicities while the inertial peak is insignificant in the anticlockwise spectra as the inertial flow is known to be clockwise in the northern hemisphere.

In general, a spectral peak of 128-hr period is dominant in the clockwise spectra while another peak of 85-hr period is noticed in the anticlockwise spectra at N, E and S locations during M-79. These peaks correspond to approximately 3-5 day oscillations in the current field. Such periodicities in the observed wind field of the lower troposphere in association with the propagating meteorological disturbances during summer monsoon seasons were reported earlier. However, these peaks could not be resolved for W location during M-79 and for all locations during M-77 due to short data lengths. During M-79, the inertial peak in the clockwise spectra was prominent at E and S locations compared to other locations. During M-77 and M-79 the peaks corresponding to diurnal and semi-diurnal periods are well resolved in both clockwise and anticlockwise spetra revealing the importance of tidal forcing in producing these oscillations. However, these peaks were less prominent at E and S locations. At N location where the stratification was strongest multiple peaks in the low frequency band are noticed both in the clockwise and anticlockwise spectra only during M-79. The absence of such a feature at N location during M-77 may be attributed to low resolution of spectra due to short data length (6 days).

4. Conclusions

During M-77 and M-79, the vertical thermal structure in the upper layers of the northern Bay of Bengal was nearly homogeneous within the observational array with the only exception of N location, However, large differences noticed in the salinity field of the upper 100 m are within the array. The upper layer salinity was relatively lower during M-77 compared to that of M-79, especially at N location. The observed flow in the upper layers was not in Ekman balance during both M-77 and M-79. The flow regime during M-79 suggests the presence of a clockwise eddy while such a feature was not noticed during M-77. The decay of the flow with depth appeared to be strongly related with the local stratification. The flow weakened rapidly with depth only during M-77 when the stratification was larger particularly at the northeastern sector of the polygon compared to the corresponding features observed during M-79. Relatively stronger flow was noticed throughout the top 200 m water column at all locations during M-79 compared to that of M-77. The rotary spectra indicated that the energy levels was about an order of magnitude higher in the clockwise spectra compared to the anticlockwise spectra suggesting the dominance of clockwise flow during both M-77 and M-79. The inertial, diurnal and semi-diurnal frequencies were also prominent in the clockwise spectra during M-77 and M-79. The inertial peak is insignificant in the anticlockwise spectra as inertial oscillations are known to be clockwise in the northern hemisphere. The spectral peaks at periods 128-hr in the clockwise spectra and 85-hr in the anticlockwise spectra during M-79 suggest approximately 3-5 day oscillations in the flow field.

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