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# Variability of wind stress and currents at selected locations over the north Indian Ocean during 1977 and 1979 summer monsoon seasons

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**सार** — मानसून-77 और मौनेक्स-79 के दौरान कालक्रमानुसार एकत्रित किए गए विभिन्न आंकड़ों का उपयोग करते हुए विरोधी मानसून ऋतुओं के अन्दर उत्तरी हिन्दमहासागर के ऊपर विभिन्न स्थानों पर दो ऋतुओं की पारस्परिक पवन प्रतिबल, पवन प्रतिबल कुंतल और पवन धाराओं का अन्वेषण किया गया है। क्रमश: सक्रिय मानसून प्रारम्भ में पूर्ण और मानसून के प्रारम्भिक अवस्थाओं के दौरान उच्च तथा निम्न सघनता के विद्यमान होने से तथा समान सिनॉप्टिक परिस्थितियों में सामान्यतः अच्छे मानसून वाले वर्ष (सन् 1977) और खराब मानसून वाले वर्ष (सन् 1979) के दौरान की तुलना में अच्छे मानसून वाले वर्ष में सतह क्षेत्र में अधिक प्रतिबल वाली पवनें और पवनधाराएं पाई गई है। अरबसागर में पवन-प्रतिबल उमिका सक्रिय अवस्था में अधिक ऋणात्मक और प्रबल पाई गई हैं जबकि बंगाल की खाड़ी में मानसून 'व्यवधान' की अवस्थाओं के दौरान शून्य के निकट पाए गए हैं। बंगाल की खाड़ी की अपेक्षा अरबसागर में पवन प्रतिबल और निकट सतह धाराओं के मध्य अधिक अच्छा तालमेल विद्यमान रहता है।

ABSTRACT. Intra-seasonal variability of wind stress, wind stress curl and currents at different locations over the northern Indian Ocean during two contrasting monsoon seasons has been investigated making use of the time series data collected during MONSOON-77 and MONEX-79. In general, the surface wind stress and near surface current fields are strong during a good monsoon year (1977) as compared to those in a bad monsoon year (1979) under similar synoptic conditions together with the prevalence of high and low intensities during active/pre-onset and break phases respectively. The wind stress curl is found to be more negative and stronger in the Arabian Sea in active phase whereas it is closer to zero during break monsoon conditions in the Bay of Bengal. A better association exists between wind stress and near surface currents in the Arabian Sea than in the Bay of Bengal.

## 1. Introduction

Knowledge of the wind stress fields over the oceans is important to understand the upper ocean circulation quantitatively. The most notable climatological mean wind stress patterns over the Indian Ocean are compiled by Hastenrath & Lamb (1979) and Bruce (1978 & 1983). Recently Wylie and Hinton (1982) have presented the ten-day average wind stress patterns over the northern Indian Ocean during May, June and July of 1979. However, the short term variability of wind stress and its influence on the oceanic currents has not been reported earlier over the northern Indian Ocean. The reason is attributed to the non-availability of time series data at different stationary locations for longer time periods. The MONSOON-77 and MONEX-79 programmes have provided an excellent opportunity to produce time-series data sets thereby facilitating the studies of the variability of wind stress on a shorter time scales at different locations in relation to different phases of summer monsoon activity.

Here, we present the intra-seasonal variability of wind stress, wind stress curl and currents during two contrast monsoon years of 1977 and 1979. An attempt is also made to understand the association between currents and wind fields in different parts of the northern Indian Ocean. In general, the monsoon activity was good in 1977 resulting in normal to excess rainfall over most of the country. On the other hand, there was a large scale deficit of monsoon rainfall during 1979 leading to drought conditions in many parts of north and central India. The seasonal rainfall departures for India as a whole was 10% below normal. For complete details on weather summary, major synoptic disturbances, advances and activity of the monsoon in 1979, the reader may consult "*Summer MONEX field phase report*" published by WMO.

## 2. Data and methodology

2.1. *List of symbols used*

- $W$ Wind speed at anemometer height (m/sec)
- $\theta$ Wind direction (deg.)
- $U$ Zonal component of wind (+ve eastward) (m/sec)
- $V$ Meridional component of wind (+ve northward) (m/sec)

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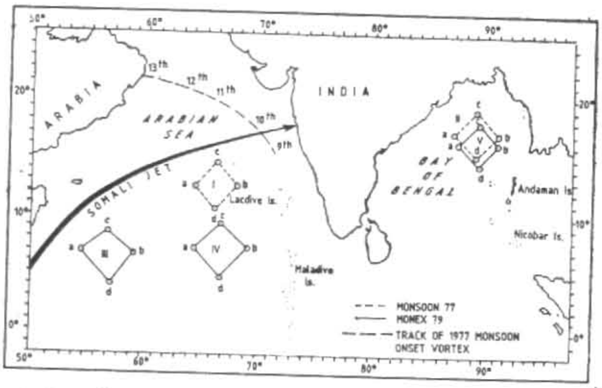


Fig. 1. Location map of the stationary polygons occupied during MONSOON-77 and MONEX-79. Thick line shows the location of the Somali jet at 1 km. Dashed line shows the track of the cyclonic storm

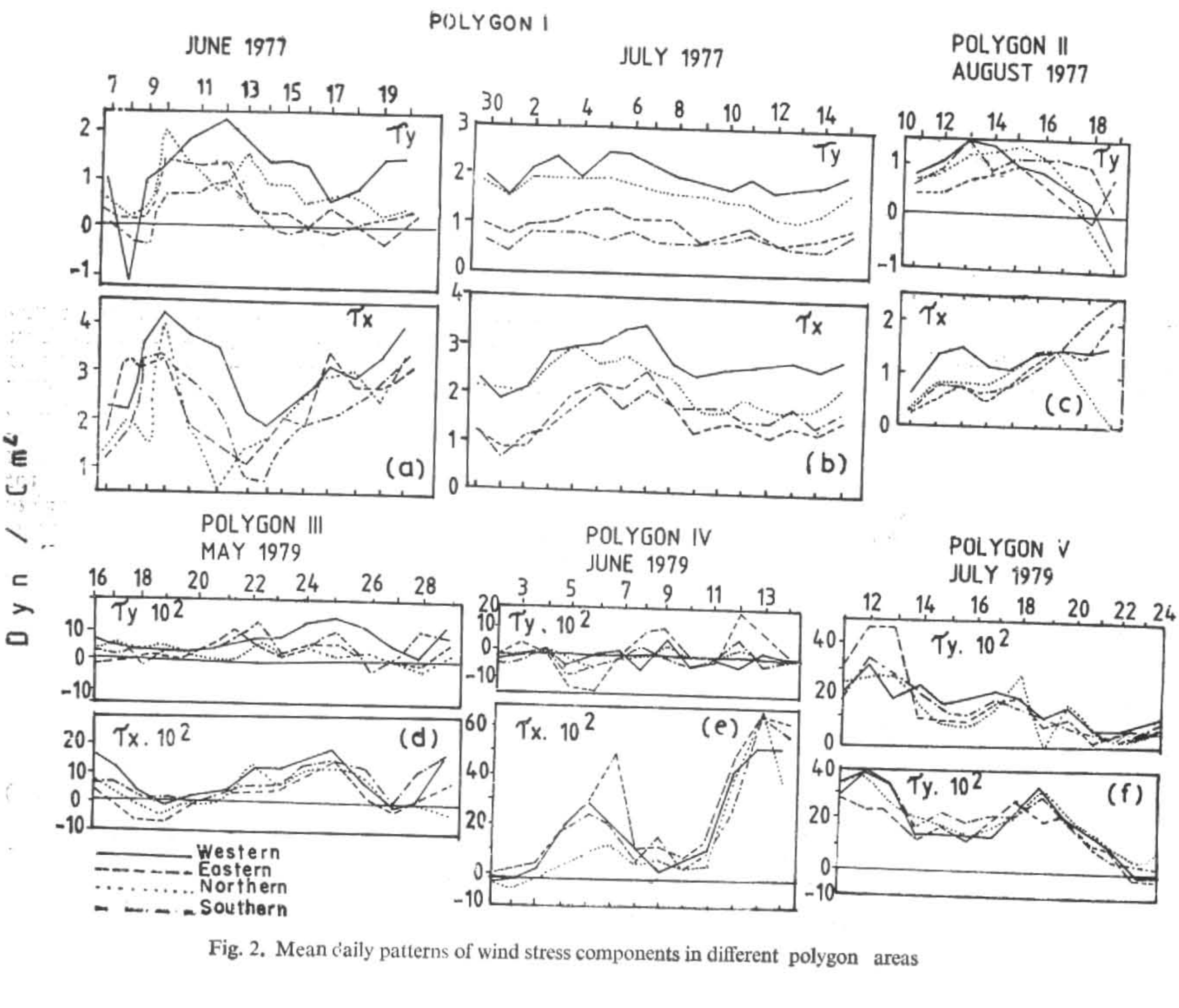


Fig. 2. Mean daily patterns of wind stress components in different polygon areas

TABLE 1

**Details of polygon areas during MONSOON-77 and MONEX-79 programmes**

| Polygon No. | Area of occupation | Duration of occupation | Name of the ship and its position | | | |
|---|---|---|---|---|---|---|
| | | | *a* | *b* | *c* | *d* |
| I | Arabian Sea (Central) | 7-20 June 1977 & 29 June-16 July 1977 | *Priboy* 12.5°N, 64.0°E | *Shirshov* 12.5°N, 68.0°E | *Okean* 14.5°N, 66.0°E | *Priliv* 10.5°N, 66.0°E |
| II | Bay of Bengal (North) | 11-19 Aug 1977 | *Shokalasky* 17.2°N, 87.0°E | *Shirshov* 17.2°N, 91.0°E | *Priboy* 19.2°N, 89.0°E | *Okean* 15.2°N, 89.0°E |
| III | Arabian Sea (West) | 16-29 May 1979 | *Shirshov* 6.5°N, 54.5°E | *Korolev* 6.3°N, 59.1°E | *Volna* 8.7°N, 57.0°E | *Priliv* 3.9°N, 57.1°E |
| IV | Arabian Sea (South) | 2-14 June 1979 | *Shirshov* 7.0°N, 64.5°E | *Korolev* 7.0°N, 69.0°E | *Volna* 9.2°N, 66.7°E | *Priliv* 4.7°N, 66.7°E |
| V | Bay of Bengal (North) | 11-24 July 1979 | *Shirshov* 16.2°N, 87.7°E | *Korolev* 16.2°N, 91.0°E | *Priboy* 18.0°N, 89.4°E | *Priliv* 14.4°N, 89.4°E |

$\tau$ Wind stress (yne/cm²)

$\tau_x$ Component of wind stress in $x$-direction (+ve eastward).

$\tau_y$ Component of wind stress in $y$-direction (+ve northward)

$C_D$ Drag coefficient

$f$ Coriolis parameter ($2\,\Omega \sin \phi$)

$\rho$ Density of air (gm/ cm³)

$\rho_0$ Density of sea water (gm/cm³)

$W_0$ Mean current speed (cm/sec)

$\theta_0$ Mean current direction

$U_0$ Zonal component of current (+ve eastward)

$V_0$ Meridional component of current (+ve northward)

$\nabla \times \tau_z$ Wind stress curl (dyne/cm³)

$h$ Depth of the mixed layer (m)

$V_M$ Vertical speed (cm/sec)

During MONSOON-77 and MONEX-79, the Russian ships occupied several stationary positions and formed as polygons at different locations over the northern Indian Ocean. The details on the positions of the ships and observational periods are given in Table 1. The locations of the polygon areas are shown in Fig. 1. Polygons I and II were formed during MONSOON-77 and the polygons III, IV and V were formed during MONEX-79. The areas of polygons II and V over the Bay of Bengal coincide approximately. At all these polygon areas, surface meteorological and time-series hydrographic observations were made at 3 hourly intervals. The data on oceanic currents at 1/2 hourly intervals were also obtained by current meters moored to the anchored buoys.

Wind stress is estimated from the well known bulk aerodynamic formula :

$$\tau=\rho C_D W^2 \qquad (1)$$

The comparisons and summaries of the $C_D$ formulations are given by Kondo (1975), Smith (1981) and Bunkar (1976). In general $C_D$ varies with wind speed and also slightly with stability of the atmosphere. Recently, Blanc (1985) has found that the scheme-to-scheme differences result in a maximum variation of 45% for an average stress of 0.2 dyne/cm². It is pointed out that there is now no single, universally accepted bulk transfer coefficient scheme. So instead of giving preference to a particular scheme, we have used a constant drag coefficient value of $1.4 \times 10^{-3}$ which is more or less an average value of the different schemes as discussed by Blanc (1985) for the present observed wind speed range.

The components of wind stress, wind stress curl and vertical motion are computed as following :

$$\tau_x = \rho\, C_D \mid U \mid W \qquad (2)$$

$$\tau_y = \rho\, C_D \mid V \mid W \qquad (3)$$

$$\tau(\nabla \times \tau_z) = \left[ \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right] \qquad (4)$$

$$\text{Vertical speed, } V_M = \frac{1}{\rho_0 f} (\nabla \times \tau_z) \qquad (5)$$

**3. Results and discussion**

3.1. *Wind stress*

The variability of the zonal and meridional components of wind stress ($\tau_x$ & $\tau_y$) in different polygon areas during 1977 & 1979 are presented in Fig. 2. Strong zonal components are seen in polygon I (Fig. 2a) and an initial peak in the beginning period is due to the influence of a moving depression over the northern Arabian Sea between 9 and 13 June. The track of depression is represented as dashed line in Fig. 1. The peak in $\tau_x$ (> 4.0 dyne/cm²) almost coincides with the onset of southwest monsoon over this region. Thereafter, $\tau_x$ increases at a steady rate due to the strengthening of the monsoon activity in this region. In general, $\tau_x$ and $\tau_y$ are found to be maximum at western location and minimum at southern location.

The stress components during an active monsoon period (30 June-15 July) in the same polygon behave more or less similar way as observed during the onset phase (Fig. 2b). Both $\tau_x$ and $\tau_y$ are found to be stronger at western and weaker at southern location respectively. This spatial variation is due to the proximity of the Somali jet core to the northern location as shown in Fig. 1.

The period of observation in the Bay of Bengal (polygon II) corresponds to break monsoon conditions. It is interesting to see that $\tau_x$ is sharply decreasing at all the locations from 15 August onwards whereas $\tau_y$ decreases at northern location only as a result of northward shift of monsoon trough (Fig. 2c). In general the daily average values of $\tau_x$ and $\tau_y$ vary from —1 to 4 dyne/cm$^2$ in polygon I whereas in polygon II they are found to vary in a short range of—1.0 to 1.0 dyne/cm$^2$.

The period of observations in the western Arabian Sea (polygon III) during 1979 represents the pre-onset phase of southwest monsoon. It is seen from the Fig. 2(d) that $\tau_x$ and $\tau_y$ are extremely small during this period and they range from —0.1 to 0.2 dyne/cm$^2$. It is interesting to notice that $\tau_x$ is negative during the first part of the period. This is due to the prevailing anticyclonic circulation centred at 5°N & 65° E during that period (Ray & Bedi 1985). It is further seen that the influence of this circulation is felt more on eastern and northern locations where $\tau_x$ is found to be more on the negative side.

In polygon IV (Fig. 2e), $\tau_x$ has a general strengthening trend whereas $\tau_y$ fluctuates around zero. There are two peaks in $\tau_x$ seen around 5 and 13 June respecitvely. The first peak does not encounter simultaneously at all the locations on the same day while the second peak occurs uniformly at all the locations in response to the disappearance of anticyclonic circulation and the onset of the southwest monsoon respectively. An increase from 0.1 to 0.7 dyne/cm$^2$ in $\tau_x$ occurs whereas no such trend is seen in $\tau_y$ during second peak period.

Incidentally the observational period at polygon V in 1979 covers the break monsoon conditions as that of polygon II in 1977. The southwesterlies become weak between 10 and 19 July over the Bay of Bengal and are dropped to those levels prevailed before the onset of monsoon. The Somali jet intensifies again from 20 to 29 July indicating the revival of monsoon activity over the northern Indian Ocean (Wylie and Hinton 1982). However in 1979 (Fig. 2f), both $\tau_x$ and $\tau_y$ have registered a fall in their intensities while in 1977, only $\tau_y$ declines eventhough the synoptic conditions (break phase) are happened to be the same during the two constrasting years. This discrepancy between 1977 and 1979 is attributed to the position of monsoon trough which is more closer to the polygon II (1977) than to the polygon V (1979). Another interesting feature observed is that the stress components are much stronger during 1977 as compared with those in 1979. The values of $\tau_x$ and $\tau_y$ have varied between 0 & 3.0 and —1.0 & +1.5 dyne/cm$^2$ respectively in 1977 while in 1979 both have varied between 0 and 0.5 dyne/cm$^2$.

### 3.2. *Wind stress curl* (*WSC*)

Wind stress curl has been evaluated for all five polygon areas during 1977 and 1979 and the results are presented in Fig. 3. During the onset phase in 1977 (Fig. 3a), initially the stress curl is positive and becomes negative

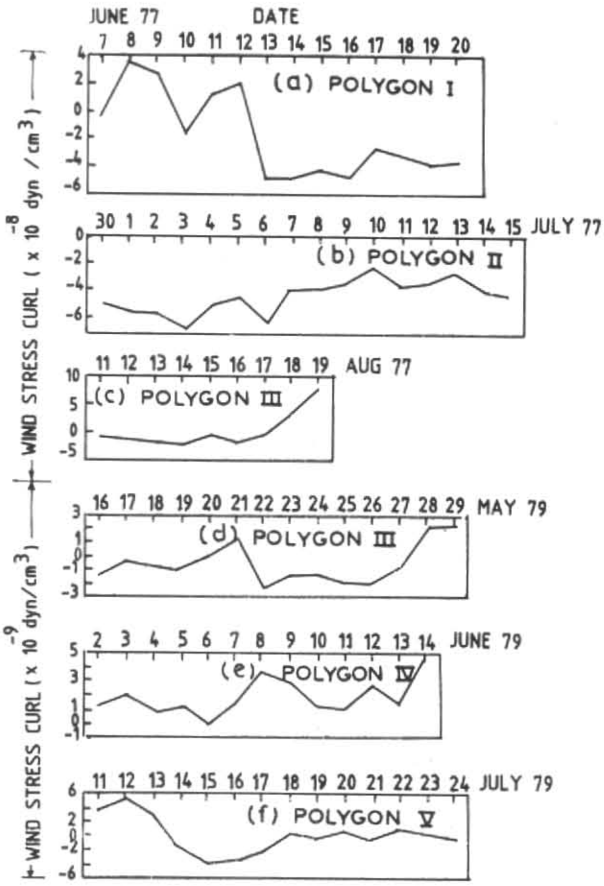


Fig. 3. Mean daily variation of wind stress curl (WSC) in all the polygon areas

after 12 June indicating a change in the wind regime due to the onset of southwest monsoon over polygon I. The positive regime between 7 and 12 June is due to the passage of a depression in the vicinity of the study area. From 13 June onwards the wind stress curl maintains negative character throughout the period but with slight variations in its intensity due to the fluctuations in the monsoon activity (Fig. 3b). During break conditions over polygon II (Fig. 3c), the WSC fluctuates around zero and becomes positive at the end of the break period and in 1979 over the same area, it varies similarly around zero especially in the later part of the break period from 18 onwards (Fig. 3f). WSC, in general, is found to be mostly negative in polygon III (Fig. 3d). This is due to the prevailing anticyclonic circulation observed in the vicinity of this study area as mentioned earlier. In polygon IV, the WSC is found to be positive throughout the period and the peak at the end of the period corresponds to the onset of southwest monsoon.

On the whole, WSC is found to be strong and negative during onset and active phases of monsoon in the central Arabian Sea and is almost zero during break monsoon conditions. From this, it is inferred that processes of strong sinking in polygon I after establishment of monsoon, weak sinking in polygon III and slight upwelling in polygon IV before the onset of monsoon and neither sinking nor upwelling exist in polygons II & V during break monsoon conditions.

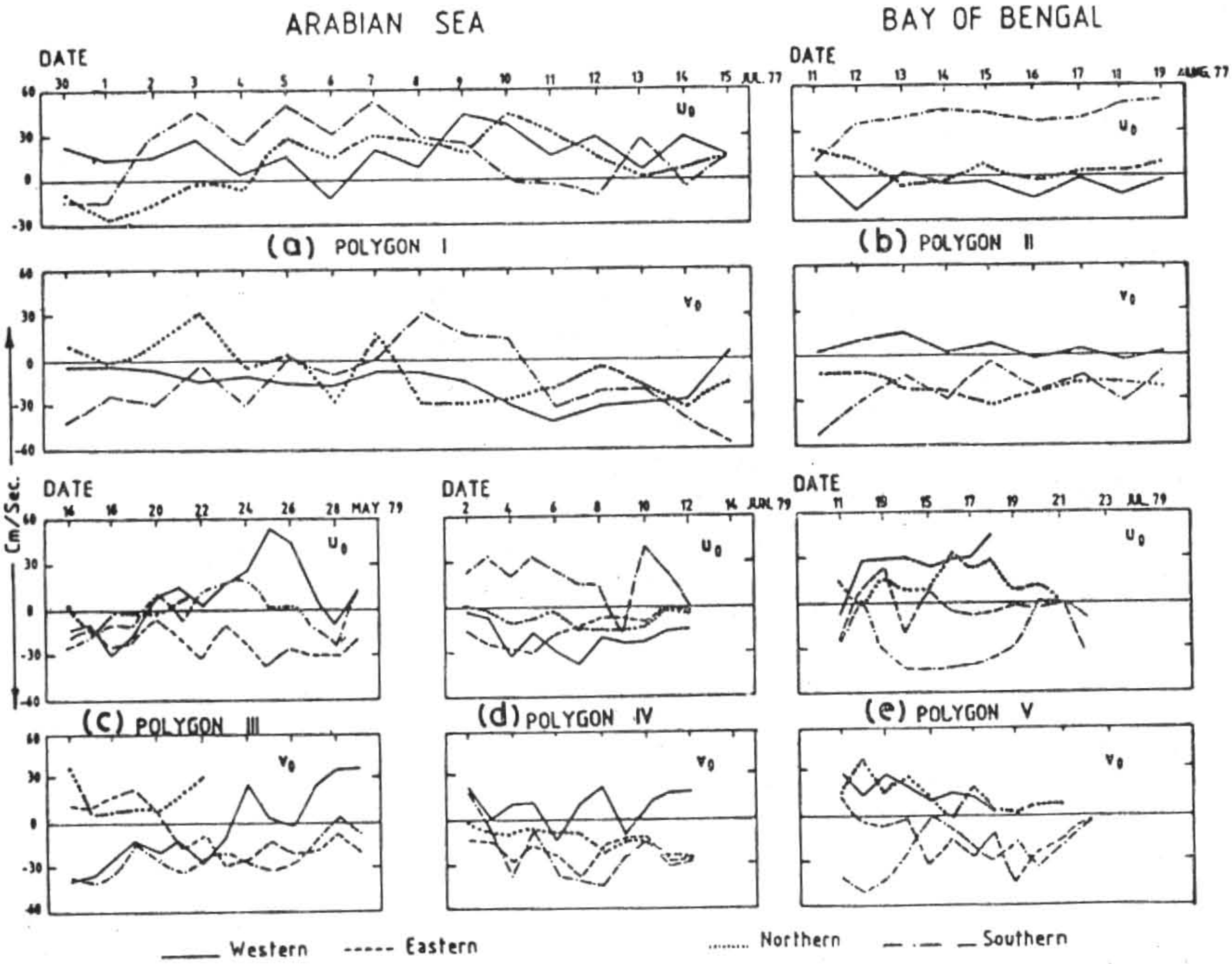


Fig. 4. Mean daily variation of the current components in different polygon areas

3.3. *Currents*

Fig. 4 shows the variability of current components ($U_0$ & $V_0$) in the polygon areas. During July 1977 (Fig. 4a) the zonal components are strong and positive while the meridional components are comparatively weak and negative giving rise to a mean flow towards 130° whereas the mean wind direction is 235°. This shows that the flow is almost at right angle to the direction of wind which is expected in steady state conditions (Gill 1982).

It is well known that the currents are generally influenced by the tidal and inertial oscillations in a given area. Pollard (1970) and Pollard and Millard (1970) have discussed in detail about setting of inertial oscillations due to impulsive winds. Fig. 4(a) clearly suggests a general two-day periodicity which is nearer to the average local inertial period of 55 hr for the polygon I area. The inertial oscillations are more felt in zonal components than in the meridional components.

In polygon II (Fig. 4b), the zonal components at southern location are comparatively strong and positive whereas at western and northern locations, they are closer to zero. In this area also, a two-day oscillation especially at western location is visualised while the inertial periodicity in this area is 40 hr.

From the fluctuations of $U_0$ and $V_0$ in polygon III (Fig. 4c), one could infer that the currents are not uniform in same quadrant at all the four locations. The mean current speeds and directions at different locations worked out are 26.3 cm/sec & 267° at western; 7.4 & 321° at eastern; 16.2 & 360° at northern and 31.1 & 193° at southern locations. There is no correlation between the wind direction and flow pattern. It is to be noted that the winds are weak southwesterlies (<5 m/sec) during this period. The stronger eastward and southward flows at the western and southern locations are the result of the clockwise gyre off Somalia which is set in mid-May and is well developed by late June 1979 (Duing *et al.* 1980).

The temporal variability of current components in polygon IV (Fig. 4d) show that the components strongly fluctuate and there is no systematic pattern as seen from the respective mean speed and directions of 23.1 cm/sec & 296° at western; 27.3 & 211° at eastern; 17.0 & 208° at northern; and 32.2 & 142° at southern locations.

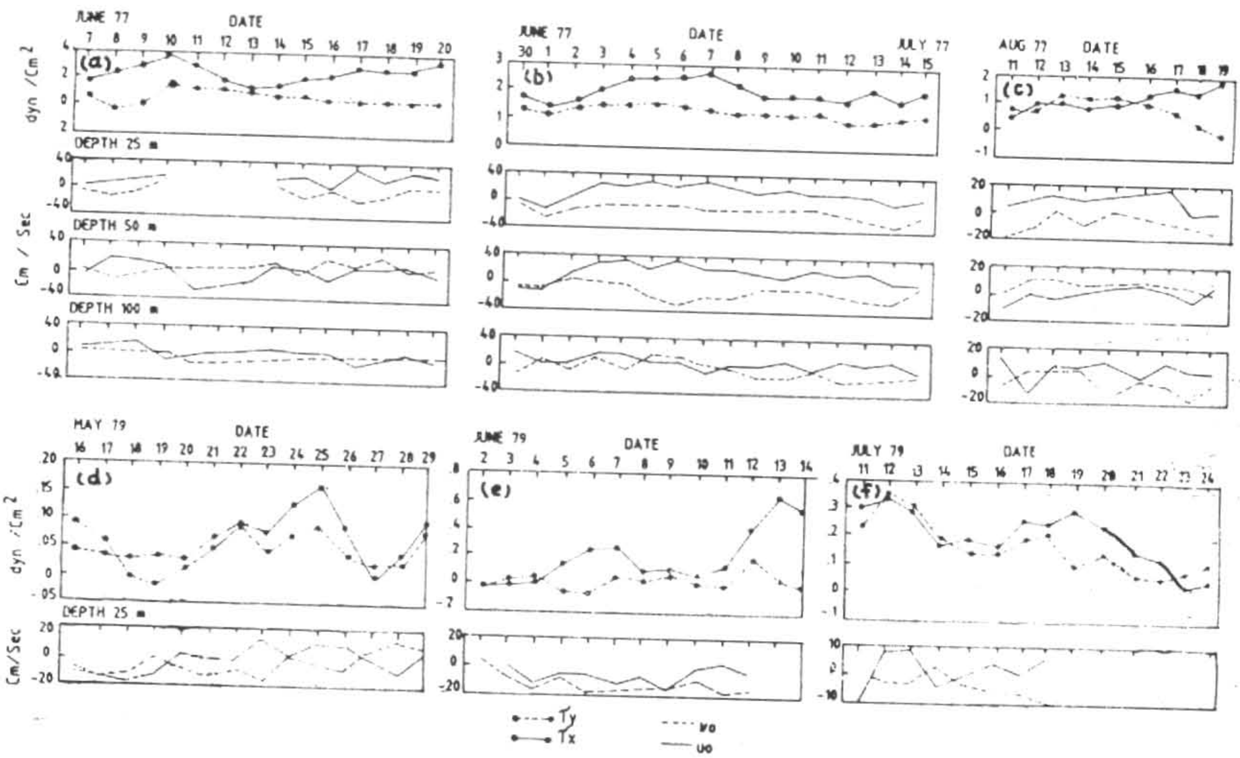


Fig. 5. Mean daily variation of wind stress and current components in all the polygon areas

Excepting at the southern one, the currents at the other locations are more or less comparable with the climatological ten-day mean surface currents obesrved during NE monsoon whereas the currents at southern location almost follow the climatological values observed in June (Cutler and Swallow 1984). This indicates that the current patterr established in response to the northeast monsoon winds are still dominant due to late onset of southwest monsoon whereas at southern location the flow pattern is affected by the southwest winds which normally advance from south to north. This trend is seen at other locations also after a few days with the advance of southwest monsoon towards north.

From the mean current speeds and directions at 25 m in polygon V (Fig. 4e), a well organised clockwise gyre is visualised centring around 16° N & 90° E (Western : 34.3 cm/sec & 74°; Eastern : 17.2 & 190°; Northern : 19.5 & 53° and Southern : 36.8 & 227°). The presence of a general anti-clockwise cell with some intra-seasonal shift seems to be seasonal feature for the north-central Bay of Bengal. Krishna Rao (1974) has inferred a counter-clockwise circulation in the head of the Bay north of 17° N and a clockwise circulation south of 17° N during fag end of summer monsoon season from satellite imageries.

### 3.4. *Relation between wind stress and currents*

The polygon mean daily values of the stress and currents are presented in Fig. 5. There is a better association between the stress and currents at 25 m in polygon I after the onset of monsoon (Fig. 5b) than that during its onset time (Fig. 5a) and the association is very poor in the other polygon areas.

In polygon I (1977) both $\tau_x$ and $\tau_y$ are strong and positive (Fig. 5b) and a good similarity between $\tau_x$ *vs* $U_0$ (25 m) exists. The meridional component of current $V_0$ (25 m) is negative and less energetic than its zonal counterpart. It is interesting to notice that $V_0$ (25 m) follows $\tau_x$ to some extent. For detailed quantification of these associations, the correlation coefficients between stress and current components have been computed. Multiple correlations are also tried with $\tau_x$ and $\tau_y$ and the results are presented in Table 2. A good correlation is observed between $\tau_x$ and $U_0$ (25 m). Similarly the correlation between $\tau_x$ and $V_0$ (25 m) is also found to be good. The correlation are further improved after taking into considerations of both $\tau_x$ and $\tau_y$ components simultaneously. At greater depths, the correlations in general become low. From these results, it is evident that the stress exerted in $x$-direction is almost equally shared by both $U_0$ (25 m) and $V_0$ (25 m) components. Under this situation one could normally expect a better correlation which is in fact seen in the multiple correlation as obtained here. However, from the magnitudes of correlations, it is said that the stress is responsible to drive a fraction of the observed current and the density stratification plays an equally important role in explaining the remaining variance in the flow field.

TABLE 2

**Correlation coefficients between wind stress and current components**

| | Simple correlation | | Multiple correlation |
|---|---|---|---|
| | $\tau_x$ | $\tau_y$ | $\tau_x$ & $\tau_y$ |
| $U_{25}$ | 0.53 | 0.17 | 0.59 |
| $V_{25}$ | 0.50 | —0.07 | 0.50 |
| $U_{50}$ | 0.18 | 0.20 | 0.29 |
| $V_{50}$ | —0.01 | —0.23 | 0.24 |

TABLE 3

**Mean variability of wind stress, stress curl, currents, vertical motion and mixed layer depths at different polygon during 1977 and 1979**

| | MONSOON-77 | | | MONEX-79 | | |
|---|---|---|---|---|---|---|
| | I | | II | III | IV | V |
| | 7-20 Jun | 30 Jun-15 Jul | 11-19 Aug | 16-29 May | 2-12 Jun | 11-22 July |
| $W$ | 12.2 | 11.95 | 9.10 | 2.18 | 3.54 | 3.90 |
| $\theta$ | 253.7 | 238.7 | 237.6 | 228.6 | 252.6 | 230.3 |
| $U$ | 11.7 | 10.2 | 7.66 | 1.64 | 3.38 | 3.0 |
| $V$ | 3.4 | 6.21 | 4.92 | 1.44 | 1.06 | 2.49 |
| $\tau$ | 2.5 | 2.4 | 1.39 | 0.08 | 0.22 | 0.26 |
| $\tau_x$ | 2.4 | 2.05 | 1.17 | 0.06 | 0.21 | 0.20 |
| $\tau_y$ | 0.71 | 1.29 | 0.75 | 0.05 | 0.02 | 0.16 |
| $10^8 (\nabla \times \tau_z)$ | —1.75 | —4.26 | 0.38 | —0.03 | 0.18 | 0.03 |
| $10^4\ V_M$ | —5.4 | —6.6 | 0.87 | —0.17 | 0.98 | 0.07 |
| $h$ | 57.4 | 97.3 | 58 | 43.2 | 43.7 | 59.5 |
| 25m $W_0$ | 17.83 | 27.8 | 12.28 | 4.85 | 14.58 | 4.28 |
| $\theta_0$ | 95.50 | 62.6 | 131.6 | 246.4 | 246.8 | 159.10 |
| $U_0$ | 17.75 | 24.69 | 9.17 | —1.94 | —5.73 | 1.53 |
| $V_0$ | —1.70 | —12.74 | —8.16 | —4.44 | —13.41 | —4.00 |
| 50m $W_0$ | 5.0 | 19.9 | 5.52 | — | — | — |
| $\theta_0$ | 62.7 | 117.6 | 77.1 | — | — | — |
| $U_0$ | 2.28 | 17.62 | 1.23 | — | — | — |
| $V_0$ | 4.42 | —9.22 | 5.38 | — | — | — |

### 3.5. *Time average polygon values*

Time average values of all the parameters for each polygon area are given in Table 3. In general, the winds are quite strong during 1977 monsoon season and are fairly closer to the climatological values (Hastenrath and Lamb 1979). It is conspicuous to see that in 1977 the winds are about two and half times stronger than in 1979 in polygons II & V which are closer to each other and the synoptic conditions are more or less same. This reflects in the stress patterns also. Similarly the wind stress curl values in polygon I are also comparable with the climatological means whereas they are very low in 1979. The mean vertical speed ($V_M$) in polygon I as computed from Eqn. (5) is found to be $-6.0\times10^{-4}$ cm/sec while the observed one as obtained from fluctuations of the mixed layer depth is about $-15\times10^{-4}$ cm/sec which is more than twice greater. The highest upward speed of about $1.0\times10^{-4}$ cm/sec is estimated in polygon IV from the mean stress curl. Rao (1984) have inferred an upward velocity of about ($1.0\times10^{-3}$ cm/sec) from the movement of 20°C isotherm (3-21 June 1979) at an area closer to the polygon IV. This suggests that (Eqn. 5) could be considered as having limited utility to obtain vertical motion on a shorter time scale under unsteady wind regime. The mixed layer depths are quite high around 100 m during fully established monsoon conditions (1977) whereas they are around 50 m just before the onset of monsoon (1979).

The mean currents at 25 and 50 m are also showing some interesting features in 1977 and 1979. In general the currents are quite strong in 1977 compared with 1979 like the wind field. From the time-average currents at 25 m in the same area (polygons II & V), it is clear that they become nearly thrice in 1977. In the central Arabian Sea at 25 m depth, the zonal components are much stronger than their meridional counterparts in 1977 and *vice-versa* in 1979. The winds and currents are opposing each other in polygons III & IV. From their mean directions, it is inferred that the southern Arabian Sea which is influenced by northeasterlies earlier maintains its inertia though weak southwesterlies are set in.

#### 4. Conclusions

(*i*) In general, the wind stress is quite stronger by about one order during the onset and active phases of monsoon in 1977 than in 1979. Similar inter-annual contrast is also noticed under break monsoon conditions.

(*ii*) The wind stress curl is found to be very strong and negative in the central Arabian Sea during the onset and active phases of southwest monsoon during 1977. It is closer to zero under break monsoon conditions in the Bay of Bengal in 1977 and 1979.

(*iii*) A better association is seen between wind stress and currents at 25 m in the Arabian Sea than in the Bay of Bengal during a good monsoon year.

(*iv*) A well organised near-surface clockwise gyre in the Bay of Bengal, centred around 16° N & 90° E during 1979, is not associated with any significant negative wind stress curl suggesting that the circulation in the northern Bay is more controlled by the factors other than wind stress.

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