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Papers

Variability of Mixed Layer Depth in the Northern Indian Ocean during 1977 and 1979 Summer Monsoon Seasons

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Influences of wind stress (τ) and wind stress curl ($\nabla \times \tau$) on the short term variability of the mixed layer depth at different locations in the northern Indian Ocean during different phases of summer monsoon activity were examined quantitatively making use of time-series data collected during MONSOON-77 and MONEX-79 programmes. After the onset of monsoon (June/July 1977) over the central Arabian Sea, wind stress together with possible sinking processes on account of negative wind stress curl and convective turnover seemed to play an important role in the development of mixed layer while in the southern Arabian Sea region, the mixed layer mainly responded to the wind stress forcing, whose magnitude though was one order less during May/June 1979. In the northern Bay of Bengal the correlation between wind stress and mixed layer was weak indicating influence of stratification caused by the fresh water discharges from Hoogly and Brahmaputra rivers.

Thermal structure variability of the Indian Ocean on monthly time scale has been studied[1]. Short-term variability studies are possible with the availability of time series data obtained during MONSOON-77 and MONEX-79 international experiments. Earlier studies[2,3] based on these field data deal with the variation of mixed layer depth in relation to various surface heat energy exchange processes in the Bay of Bengal and Arabian Sea. Simulations[4] are made on the observed cooling and deepening of the mixed layer in the central Arabian Sea during the onset of the summer monsoon in 1977 making use of a unidimensional numerical model. The evolution of thermal structure in the upper layers of the central Arabian Sea has been investigated[5]. However, none of these studies have critically examined the relation between mixed layer depth and wind stress though the latter is also one of the important forcing functions.

The objective of the present study is to examine in detail the association between the fluctuations in wind stress and wind stress curl on the variability of the mixed layer depth (MLD) in the northern Indian Ocean during different phases of 2 contrasting summer monsoon seasons. The role of other influencing factors like stratification, advection is also briefly discussed.

Materials and Methods

During MONSOON-77 and MONEX-79, the Russian ships occupied several stationary positions and formed as polygons (Fig. 1) in different areas of the northern Indian Ocean. Time series data collected at 3 h interval on surface meteorological parameters such as wind speed and direction, surface pressure and sea surface temperature and subsurface bathythermograph data were made use of in this study. The main synoptic surface atmospheric conditions were described[6] during the period of observations (1977 and 1979). Polygons I and II were formed during MONSOON-77 whereas polygons III to V were formed during MONEX-79. In the vicinities of these polygons current profiles at 30 min interval were obtained through deployment of current meters moored to anchored buoys.

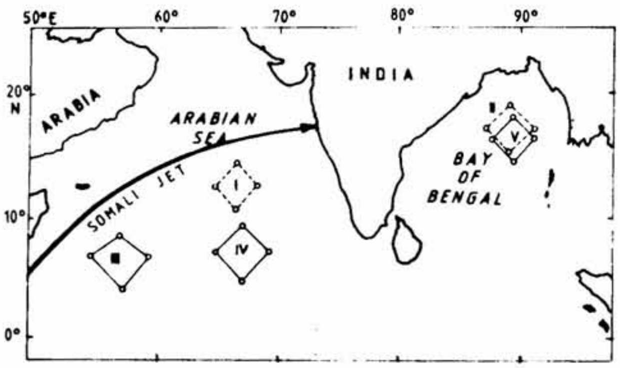

Fig. 1—Location of polygons in the north Indian Ocean during MONSOON-77(---) and MONEX-79(——) programmes

Mixed layer depth is taken as the depth of the isotherm which is 1°C less than the surface temperature. Wind stress is estimated from the well known bulk aero-dynamical formula:

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

where τ is wind stress (dyn.cm^{-2}); ρ is density of air; C_D is the dimensionless drag coefficient and W is wind speed at anemometer height (m.sec^{-1}). Summaries and comparisons of the C_D formulations have been presented[7-9]. In general C_D increases with wind speed and the stability of the atmosphere. Blanc[10] has compared various coefficient schemes and found that the scheme-to-scheme differences would result in a maximum variation of 45% for an average stress determination of 0.2 dyn.cm^{-2}. Since there is no single, universally accepted bulk transfer coefficient scheme, throughout a constant drag coefficient value of 1.4×10^{-3} has been assigned, which is nearly in agreement with the average value of the different schemes as discussed by Blanc[10] for the observed range of wind speeds.

The components of wind stress and wind stress curl are computed from the following equations:

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

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

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

where τ_x and τ_y are components of wind stress in x-direction (+ve eastward) and y-direction (+ve northward) respectively; U is zonal component of wind (+ve eastward); V is meridional component of wind (+ve northward); $\nabla \times \tau$ is wind stress curl (dyn.cm^{-3}).

Results and Discussion

The polygon areas (Fig. 1) of the present study broadly cover central and southern parts of the Arabian Sea and northern Bay of Bengal. Table 1 presents monthly climatic means of the MLD[1] in these regions together with the observed average MLD values during the study period. The average MLD values observed at the polygon are in general comparable with the climatological values in the respective areas. In the central Arabian Sea, MLD is maximum in August. The shallow depths corresponding to pre and postmonsoon seasons are attributed to high net radiational heating. In the northern Bay of Bengal, the maximum depth (≈ 80 m) is in winter due to convective instability on account of high surface cooling. The increase in MLD during SW monsoon is not seen profoundly in the Bay of Bengal in contrast to that in central Arabian Sea. MLD is less variant in the southern Arabian Sea compared to the above 2 regions.

Mixed layer depth and wind stress—The daily variability of MLD and wind stress at different polygons during different phases of monsoon activity is depicted in Fig. 2. Initially MLD was around 45 m in polygon I (Fig. 2A) before onset of monsoon in 1977. It deepened at a faster rate to around 75 m during the onset phase and further it slowly in-

Table 1—Monthly Variation of MLD (m) in Northern Indian Ocean

Month	Central Arabian Sea		Southern Arabian Sea		Northern Bay of Bengal	
	Climato-logical* MLD	Observed MLD	Climato-logical* MLD	Observed MLD	Climato-logical* MLD	Observed MLD
Jan.	50		38		80	
Feb.	55		50		79	
March	56		54		51	
April	50		50		41	
May	46		41		48	
				P(III) 43		
June	53		48		52	
		P(I) 62		P(IV) 45		
July	75		58		67	
		P(I) 98				P(V) 59
Aug.	79		60		71	
						P(II) 58
Sept.	70		55		61	
Oct.	50		50		56	
Nov.	40		40		50	
Dec.	38		40		54	

P = Polygon; *After Colborn[1].

creased to about 100 m after the monsoon was fully established over the region. The wind stress in the polygon varied between 1 and 4.5 dyn.cm^{-2} (Fig. 2B). It is interesting to see that high wind stress was encountered at northern and western locations of the polygon reflecting the effect of their near proximity to the Somali Jet as shown in Fig. 1.

In polygon II (Fig. 2G) the observational phase represented break monsoon condition over the Bay of Bengal. All the 4 corners of the polygon showed mixed layer depths of varying magnitudes. The lowest MLD ($\approx$ 35 m) was distinctively seen at the northern location while at the other 3 locations MLD was more or less same ($\approx$ 60 m). However, the wind stress was almost uniform (2 dyn.cm^{-2}) at the 4 corners of the polygon II (Fig. 2H). This shows that some force other than wind stress is responsible for the exceptionally shallow nature of MLD at northern location. In the northern Bay of Bengal especially during SW monsoon period (June-September) strong pycnocline formed as a result of fresh water discharge from the rivers Brahmaputra and Hoogly leading to a stable stratification in the upper layers of the water column. It is observed that at northern location in polygon II average salinities were as low as 31×10^{-3} and at other locations they were around 33.4×10^{-3}. Similar feature was reported by Rao[2] in this region. The observational period in polygon III represented premonsoon condition during 1979. In general the maximum ($\approx$ 50 m) and minimum ($\approx$ 30 m) values were at southern and northern locations respectively (Fig. 2C). Here, the magnitudes of the wind stress were of one order less than those observed during onset phase of monsoon 1977 (Fig. 2D).

The major part of the study period at polygon IV is also considered as the pre-onset phase since the monsoon in 1979 was set only on 12 June 1979 over the southern Arabian Sea as seen from the sudden increase in wind stress (Fig. 2F). Here the spatial variability in MLD was almost negligible (Fig. 2E) in contrast to that in polygon III. The sudden MLD deepening in the entire polygon IV during 12-14 June 1979 was clearly associated with a sudden increase in the wind stress from 0.1 to 0.7 dyn.cm^{-2} during onset period (Fig. 2E and F). There was a highest positive correlation (0.78) at 98% significance level between MLD and wind stress during the pre-onset period (2-14 June 1979) at polygon IV reflecting the positive response of the mixed layer to the sudden increase in wind force at the time of onset.

At polygon V which is more or less coinciding with the same area of polygon II (Fig. 1) the weather conditions represent a lull in the monsoon activity similar to that in 1977. Though the wind stress was

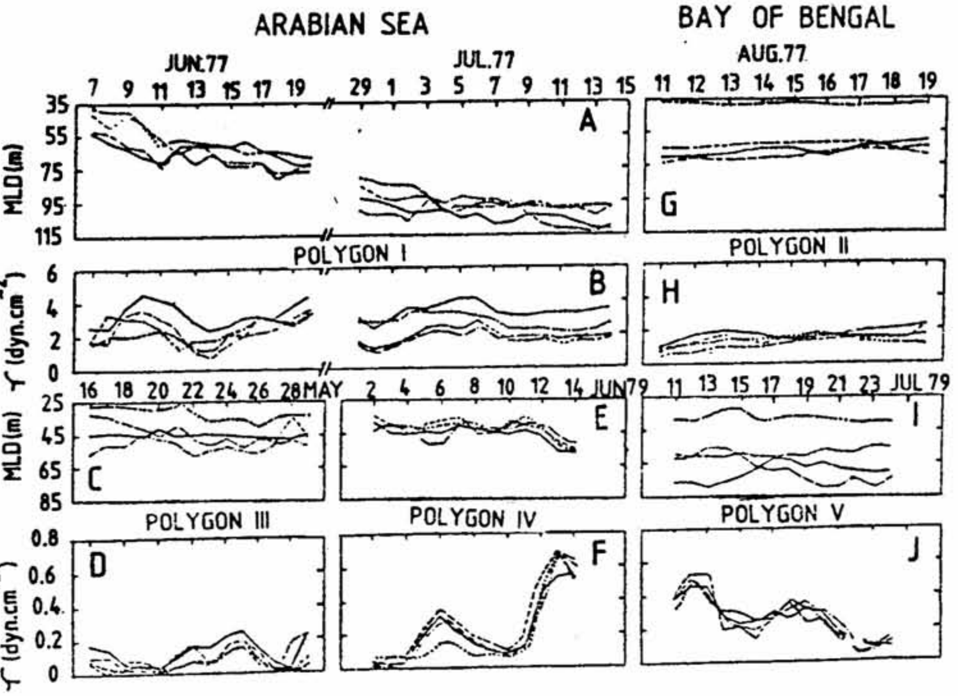

Fig. 2—Daily variations of mixed layer depth (MLD) and wind stress (τ) in the Arabian Sea (A-F) and Bay of Bengal (G-J) [Western, —; eastern, - - -; northern, ...; southern, —.—.—]

low (Fig. 2J) as compared to that in 1979, its general decreasing trend at polygon V did not influence MLD which was rather steady (Fig. 2I). Again at the northern location lowest MLD values were encountered. Interestingly, the north-south gradient in MLD was maintained in 1977 and 1979 (polygons II and V) suggesting that stratification plays an important role on the variability of MLD in the northern Bay of Bengal. The weak relationship between wind stress and MLD in the northern Bay of Bengal (Fig. 2G-J) was clearly seen from negative correlation coefficient values (Table 2) obtained in 1977 and 1979.

A scatter diagram (Fig. 3) is plotted between MLD and wind stress values observed at all the polygons in order to deleniate the correlations further. It is evident from the diagram that the influence of wind stress on MLD was more in polygons III and IV as seen from the near linear relationships. On the other hand in polygons II and V, which represent the Bay of Bengal, a negative relation between wind stress and MLD i.e. a decreasing trend in MLD with increasing wind stress, was observed suggesting that the upper layers of the Bay of Bengal are quite stable to affect the wind induced turbulent mixing. In the central Arabian Sea the influence of wind stress was reduced in the later part of the monsoon season (July 1977) when the mixed layer itself was quite deeper. For example, MLD was more or less steady around 100 m inspite of wide variations in wind stress values betwen 1.8 and 4 dyn.cm^{-2}. These results indicate that the wind forcing on

Table 2—Correlation Coefficients between MLD *vs* τ and MLD *vs* WSC at Different Polygon Areas

	Polygon I		Polygon II August 1977	Polygon III May 1979	Polygon IV June 1979	Polygon V July 1979
	June 1977	July 1977				
MLD vs τ	0.06	0.04	−0.63	0.52	0.78	−0.51
MLD vs WSC	−0.21	0.59	−0.32	−0.72	0.52	0.21

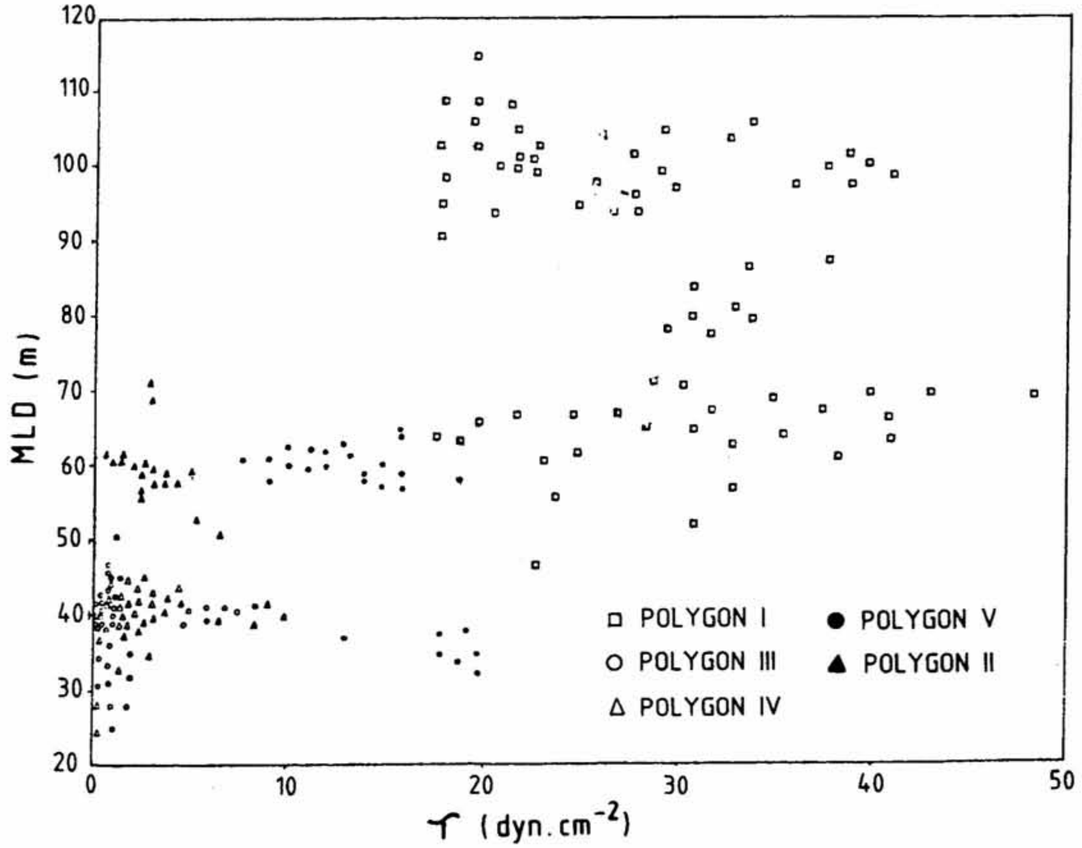

Fig. 3—Scatter diagram between MLD and τ

mixed layer development depends more on the initial value of MLD in the Arabian Sea while in the Bay of Bengal, fresh water discharges from the rivers gave rise to larger vertical gradients in density which in turn causes the upper water column stably stratified.

MLD and wind stress curl—MLD is also influenced by the wind stress curl (WSC) inducing upward/downward (Ekman pumping) velocities in the upper ocean. From Fig. 4A it is seen that maximum negative wind stress curl was in the central Arabian Sea as compared to the other parts of the northern Indian Ocean. This helps further in the stronger development of MLD in this region. There was a clear change in its regime from initial positive values to the later negative values. The rate of change was higher in June than in July suggesting that WSC plays an additional role in the development of mixed layer. In polygons III and IV, WSC role cannot be ascertained as the magnitude was one order less and also there was no clear trend in WSC regime (Fig. 4C and D). In the Bay of Bengal polygons, comparison of MLD and WSC curves indicates less influence of the former as MLD was comparatively steady in spite of changes from one regime to other (Fig. 4B and E). For example, in polygon II between 17 and 19 August 1977 there was drastic change in WSC regime from -1 to about 0.8 dyn.cm^{-3} while the mixed layer was steady around 60 m (Fig. 4B). Similarly in 1979 also when WSC was remarkably changed from 0.6 to about -0.4 dyn.cm^{-3} between 12 and 15 July 1979, mixed layer was not increased but instead a slight decrease was seen (Fig. 4E). These results suggest that central Arabian Sea has a better relation between WSC and MLD than the other parts of the north Indian Ocean.

The central Arabian Sea area corresponds to the zone of maximum evaporation where the cooling of sea surface[11] is of the order of 4° to 5°C. So one cannot rule out the possible role of thermal forcing in the deepening of the mixed layer due to net heat loss across the sea surface. In order to identify the dominating forcing function in this region the Monin-Obukhov length (L) was computed. The main input data were obtained from Rao *et al.*[12] and the ratio L/h was computed according to Niiler and Kraus[13]. It is found that the average ratio (L/h) was < 1 indicating that central Arabian Sea regime receives substantial energy from net heat energy exchange at the sea surface apart from wind force alone in the development of MLD. This supports the view of Rao[14] who studied MLD variability with the same data set. However, one has to be cautious in concluding this, as the initial h value during July 1977 was higher in this region because the observational period represented the onset/active phases of monsoon as compared

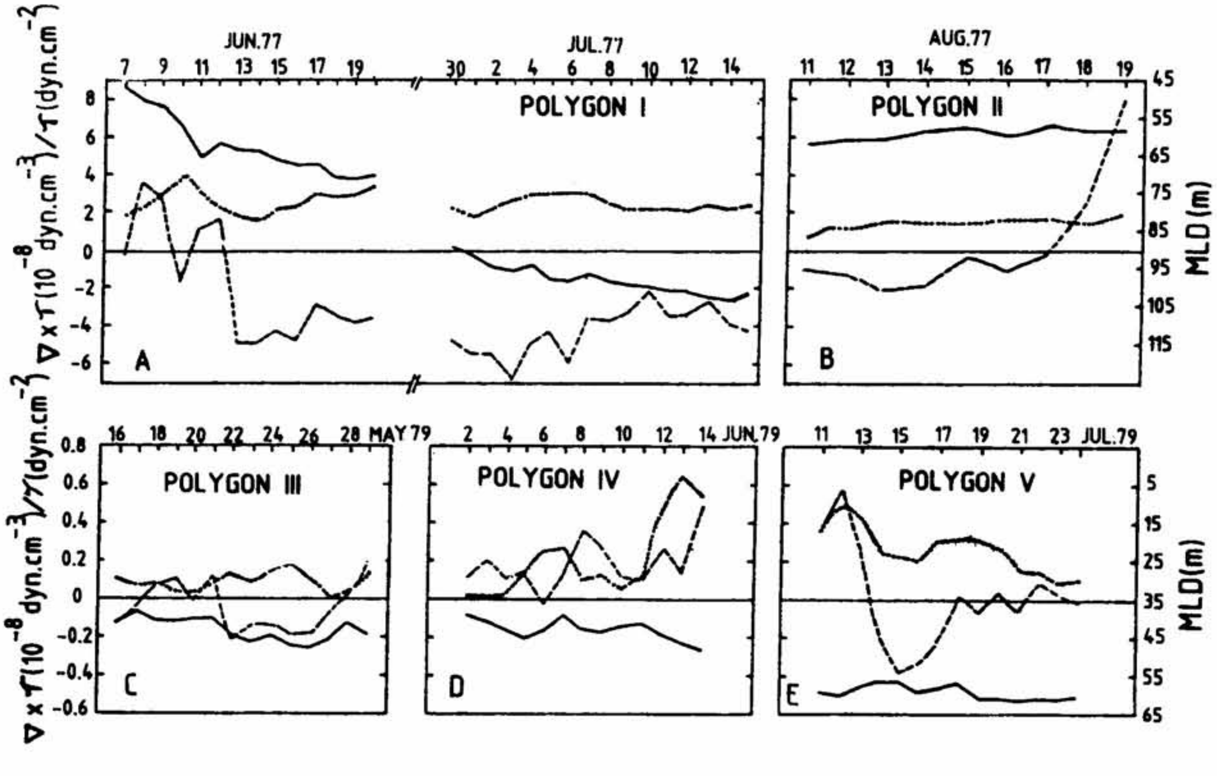

Fig. 4—Daily polygon means of wind stress curl (WSC), MLD and wind stress (τ) in the Arabian Sea (A,C,D) and Bay of Bengal (B,E) [MLD, —; τ, ...; WSC (∇×τ), - - -]

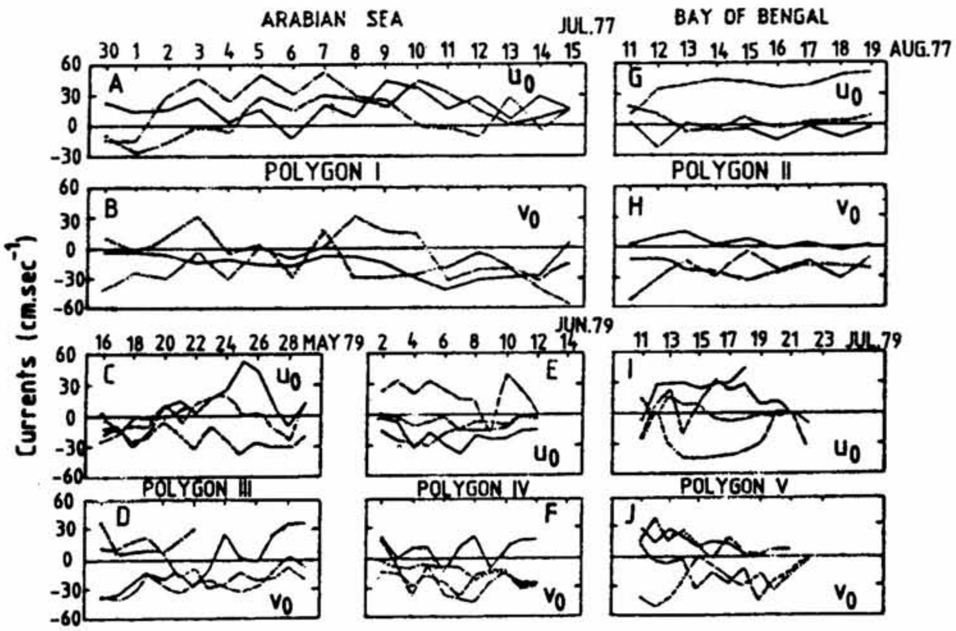

Fig. 5—Daily variation of zonal (U_0) and meridional (V_0) components of currents observed at 25 m in the Arabian Sea (A-F) and Bay of Bengal (G-J) [Western, —; estern, - - -; northern, ...; southern, —·—·—]

to the initial low h values in 1979 when the observations were mainly taken before the onset of SW monsoon. So these conclusions are not of general nature and applicable specifically for a particular location at a particular time.

Currents—Fig. 5 shows the variability of surface current components (U_0 and V_0) at different locations during 1977 and 1979. Due to non-availability of data, currents during the entire onset phase of 1977 in polygon I as well as at eastern location during 1977 could not be presented.

At polygon I during the active phase (July 1977), the zonal components were positive and slightly stronger than their meridional counterparts which were seen broadly negative (Fig. 5A and B). This shows that the general flow in the polygon is towards southeast (130°). The observed mean direction of wind in this region was 235° indicating the dominance of the Ekman transport under steady state conditions[15]. In polygon II, meridional components were stronger than those of zonal in the northern location and *vice versa* in southern location (Fig. 5G and H). This flow pattern encourages neither large scale convergence nor divergence in this region and as such it may not influence MLD to a greater extent. At polygon III, the zonal components at western location gradually became positive with time while at eastern location they were more negative (Fig. 5D). This trend favours the convergence in this area and thereby deepening of MLD. Model study by Shetye[16] stressed the significance of advection in the southern Arabian Sea during monsoon season on a seasonal scale. A careful examination of the currents in polygon IV reveals that the pattern is neither conducive for convergence nor divergence and this helps in maintaining the steady nature of MLD (Fig. 5E and F). In polygon V, the setup of zonal and meridional current components encourages a deepening of MLD (Fig. 5I and J). However, this set-up is not in consonance with WSC emphasising its lesser role on MLD in northern Bay of Bengal. It is known that a clock-wise circulation prevails in the northern Bay of Bengal during SW monsoon season. In fact a clockwise gyre has been noticed[6] from the observed currents in the same area. So one would expect deepening of mixed layer as a result of convergence which is not seen here. This again supports present observations that stratification plays a dominant role than all the other forcing parameters.

In the central Arabian Sea (polygon I) during onset and active phases of the monsoon heat energy exchange plays a significant role rather than the wind stirring. In the western Arabian Sea (polygon III) during pre-onset of summer monsoon wind stress curl plays a dominant role in the deepening of the mixed layer. In the southern Arabian Sea (polygon IV) mechanical stirring imparted by wind stress affects MLD variability while in the northern Bay of Bengal (polygons II and V) the influence of wind forcing is negligible indicating the vital role of stratification associated with the fresh water discharge from the rivers.

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