Ekman pumping velocity and depth of surface mixed layer of the north Indian Ocean during southwest monsoon

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Received 25 September 1989; revised 8 August 1990

Effect of Ekman pumping velocity on the variability of mixed layer depth is considered using sub-surface and marine meteorological data. Relatively shallow mixed layer is found during May due to the influence of summer heating. From June onwards, in general, deep mixed layer is found in the regions of negative Ekman pumping velocity, while shallow layer is observed in the regions of positive Ekman pumping velocity. However, during August and September in the Arabian Sea, horizontal advection of surface waters and convective overturning caused by buoyancy flux along with the stress curl field appear responsible for the deepening of mixed layer. During August, shallow layer, which is observed in the region of negative Ekman pumping velocity along the central region of east coast of India, is probably due to the stable stratification caused by fresh water discharge from the rivers—Krishna, Godavari and Mahanadi. Profound variations in both Ekman pumping velocity and mixed layer depth are noticed over the Arabian Sea in contrast to the Bay of Bengal.

The study on temporal and spatial variations in Ekman pumping velocity and mixed layer depth of north Indian Ocean related to Asiatic summer monsoon assumes special significance, since circulation, during this season, is marked by presence of a strong curl of wind stress field which can be expected to influence the vertical thermal structure of the upper ocean. Earlier studies on this aspect are limited to specific regions or to short time periods. The objective of the present investigation is to study mean monthly variations of Ekman pumping velocity and its association with the variability of surface mixed layer depth of north Indian Ocean during southwest monsoon (May through September).

Materials and Methods
Surface and sub-surface data from 1970 to 1977 were collected over north Indian Ocean (Fig.1) during southwest monsoon (May through September). The data sources were National Oceanographic Data Centre (NODC), Washington DC, USA and Indian Daily Weather Reports (IDWR). The mixed layer depth, depth at which the temperature is lower by 1°C to the surface temperature, was obtained from MBT and XBT data supplied by NODC. Marine meteorological data were collected from IDWR charts and NODC. The basic parameters extracted from the combined data set were wind speed, wind direction, air and sea surface temperatures. In addition to this, associated time and space parameters such as year, month, day, hour, latitude, longitude were also extracted. Duplicate records, with identical date, place, air and sea surface temperature and wind data, were deleted. The data were sorted in ascending order on latitude key and climatic monthly averages of each parameter with 2° square spatial resolution were obtained. The necessary computer software was developed by one of the authors (VSN). Missing values were estimated using linear interpolation in the zonal direction.

Utilising the marine meteorological data, components of wind stress \( \tau_x \) and \( \tau_y \) were obtained from the following equations:

\[
\tau_x = \rho_a C_D U (U^2 + V^2)^{1/2} \quad \ldots (1)
\]

\[
\tau_y = \rho_a C_D V (U^2 + V^2)^{1/2} \quad \ldots (2)
\]

where \( \tau_x \) and \( \tau_y \) are wind stress (dyn cm\(^{-2}\)) in \( x \)-direction (positive eastward) and \( y \)-direction (positive northward) respectively; \( U \) is zonal component of wind (positive eastward); \( V \), meridional component of wind (positive northward); \( \rho_a \), air density; \( C_D \), non-dimensional drag coefficient. \( C_D \) is function of both wind speed and stability. In general, \( C_D \) increases with wind speed and stability of atmosphere. In this study, \( C_D \) value was calculated from the second degree polynomial as suggested by Hellerman and Rosenstein since the value obtained...
from this formula is almost equivalent to the Bunker's table\textsuperscript{9} which can be applicable for wide range of wind speed and stability variations

$$C_D(M, \Delta T) = 0.934 \times 10^{-3} + 0.788 \times 10^{-4} M + 0.868 \times 10^{-4} (\Delta T)$$

$$- 0.616 \times 10^{-6} M^2$$

$$- 0.120 \times 10^{-5} (\Delta T)^2$$

$$- 0.214 \times 10^{-5} M (\Delta T)$$ \ldots (3)

where $M$ is $(U^2 + V^2)^{1/2}$; and $\Delta T$, air-sea temperature difference in degree centigrade. Ekman pumping velocity ($W_E$) was calculated using the formula\textsuperscript{10}

$$W_E = \frac{1}{\rho_0 f} \text{curl} \tau$$ \ldots (4)

where $\rho_0$ and $f$ are the water density (1026 kg m\textsuperscript{-3}) and coriolis parameter respectively. In the regions below 4°N, $f$ was calculated\textsuperscript{11} assuming $\sin \phi = \phi$, where $\phi$ is latitude in degrees.

**Results and Discussion**

Distribution of Ekman pumping velocity shows that in May, positive values, which are conducive to the upwelling, are found along the western and eastern parts of the Arabian Sea and the Bay of Bengal (Fig.2A). Upwelling ($1.0 \times 10^{-3}$ m sec\textsuperscript{-1}) is observed off the east coast of Arabia and off the Somalia. This high upward movement along this region is probably caused by the onset of strong low level jet\textsuperscript{12} which drives surface waters northward leading to upwelling. Downwelling is found along the equatorial regions.

In June, southwest monsoon is fully established over the study region. As a result, vertical velocity also increases (Fig.2B). Since the intensity of Somali Jet increases, upwelling along the western Arabian Sea is increased. Under the influence of anti-cyclonic vorticity, downwelling is observed in the central and equatorial Arabian Sea. The upward movement observed all along the east coast of India is due to the persistence of strong southwesterly winds. Prominent downwelling is noticed along the equatorial Bay of Bengal. Earlier studies\textsuperscript{13} also reveal convergence of surface currents during southwest monsoon season in this region.

In July, southwest monsoon is at its peak (Fig.2C). However, the pattern more or less remains unchanged. Although the same pattern is maintained in August also, except off the west and east coasts of India where negative values are found, the values have decreased considerably over the Bay of Bengal during this month (Fig.2D).

Since southwest monsoon starts to retreat in September, the values have further, decreased (Fig.2E). However, in this month also, the same pattern is maintained.

Distribution of mixed layer depth indicates relatively shallow mixed layer in May over north Indian Ocean (Fig.3A). During this month, winds over north Indian Ocean are comparatively less stronger and surface waters are influenced by summer heating. As a result, mixing is confined to shallow
Fig. 2—Ekman pumping velocity (1 × 10^{-5} m sec^{-1}) for the month of May (A), June (B), July (C), August (D) and September (E)

Fig. 3—Mixed layer depth (m) for the month of May (A), June (B), July (C), August (D) and September (E)
layers. Deep mixed layer is noticed along the equator and this layer becomes shallow towards north. Relatively shallow layer is found along the western boundaries of the Arabian Sea and the Bay of Bengal due to upwelling.

Mixed layer relatively deepens during June (Fig.3B) and deep mixed layer is found in the central and southern regions of the Arabian Sea and along equatorial Bay of Bengal. Shallow layer is observed in the northern parts of both the Arabian Sea and the Bay of Bengal. In general, the observed variations of mixed layer depth are in fair agreement with variations of Ekman pumping velocity which are caused by the prevailing south west monsoonal circulation.

In July, the pattern is changed over the Arabian Sea. Deep layer is noticed in its central part and this layer shallows radially (Fig.3C). The deep layer in central Arabian Sea is probably due to the downwelling observed in this region. The depth of the layer also increases in this region as compared to preceding month. However, in the Bay of Bengal, the situation is different. The depth of mixed layer in its southern parts decreases in contrast to the previous month.

Although the pattern is more or less same as compared with the previous month, during August, mixed layer depth increases in central Arabian Sea (Fig.3D). On the other hand, the Ekman pumping velocity decreases over this region. Hence, the deepening of layer in this region is probably caused by the factor(s) other than wind stress curl field. The central Arabian Sea area corresponds to the zone of maximum evaporation where cooling of the sea surface is of the order of 4°C to 5°C during the period. Therefore the convective overturning caused by the heat exchange over the surface has influenced this deepening of layer. Moreover, mixed layer is maximum at 10°-12°N and 60°-62°E while negative Ekman pumping velocity is maximum at 5°-10°N and 55°-60°E. The presence of maximum layer depth, associated with relatively smaller magnitude of negative Ekman pumping velocity, may be due to the influence of eastward horizontal advection of surface cold waters from the Somali region during this month. Model study of Shetye has stressed the role of advection in the southern Arabian Sea during monsoon season on a seasonal scale. In the Bay of Bengal, mixed layer becomes shallow towards northwest from equator. Shallow layer is observed along the central region of east coast of India, where, in contrast, negative values of Ekman pumping velocity are noticed. This shallow nature of the mixed layer can be explained due to the stable stratification as a result of fresh water discharge from the rivers—Krishna, Godavari and Mahanadi.

In September (Fig.3E) also, the same pattern is maintained. However, the values in the central Arabian Sea are decreased by 10 m. In this month also, the region of maximum mixed layer depth is noticed in the region of relatively lower magnitudes of negative Ekman pumping velocity. Due to non-availability of data, isolines in the northern Bay of Bengal could not be drawn.

From the results, it is observed that summer heating dominates in the development of mixed layer during May. From June onwards, in general, deepening of mixed layer is caused by the field of wind stress curl. However, in August and September, in the Arabian Sea, horizontal advection of surface waters from western Arabian Sea and convective overturning caused by buoyancy flux along with the stress curl field may influence the variability of mixed layer. Stable stratification associated with fresh water discharge from the rivers is responsible for the shallow mixed layer in western Bay of Bengal.

Acknowledgements

One of the authors (VSN) expresses his gratitude to CSIR, New Delhi for financial assistance.

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