

Wind stress, curl and vertical velocity in the Bay of Bengal during southwest monsoon, 1984

M T Babu, A K Hebalekar* & C S Murty

National Institute of Oceanography, Dona Paula, Goa 403 004, India

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Wind distribution observed during southwest monsoon of 1984 has been used to derive the mean wind stress for the season at every 1° square grid and curl over the Bay of Bengal. Two regions of maximum wind stress are present over the Bay of Bengal. Variability of wind components is compared with that derived from the wind field, given in the climatological atlas. Zonal component of the climatological and observed wind field has a maximum stress along 15°N lat. along which the computed vertical velocity field presents a negative maximum (sinking). The possible mechanisms influencing the surface layer dynamics have been discussed.

Studies related to the atmospheric forcing at the air-sea interface¹⁻³ suggest that the water circulation at the surface layer is primarily influenced by the vertical component of the wind stress curl. The surface wind stress curl acting over the sea surface balancing with the Coriolis force drives the surface layers horizontally as expressed by the Sverdrup relation. The horizontal shear in the wind field and the subsequent vorticity generated induce the horizontal transport of the waters. This in turn drives the deeper waters upward (Ekman pumping) which can be measured as a function of the wind stress acting over the sea surface. As a result, regions of convergence and divergence form in the upper layer which change the density fields and cause the wind driven currents.

In the Bay of Bengal, the currents driven by the prevailing wind system and the existing circulation show significant changes during the southwest monsoon period⁴. This variability of the upper layers influences the air-sea interaction process since the momentum and heat fluxes change along with the onset of southwest monsoon. It is the wind stress and the wind stress curl which undergoes periodic change during the southwest monsoon period. The present study analyses the wind stress and the curl over the Bay of Bengal in order to determine the variability of the surface layer processes.

Materials and Methods

The wind data collected from the study area (Fig. 1) during 31 July to 6 October 1984 using

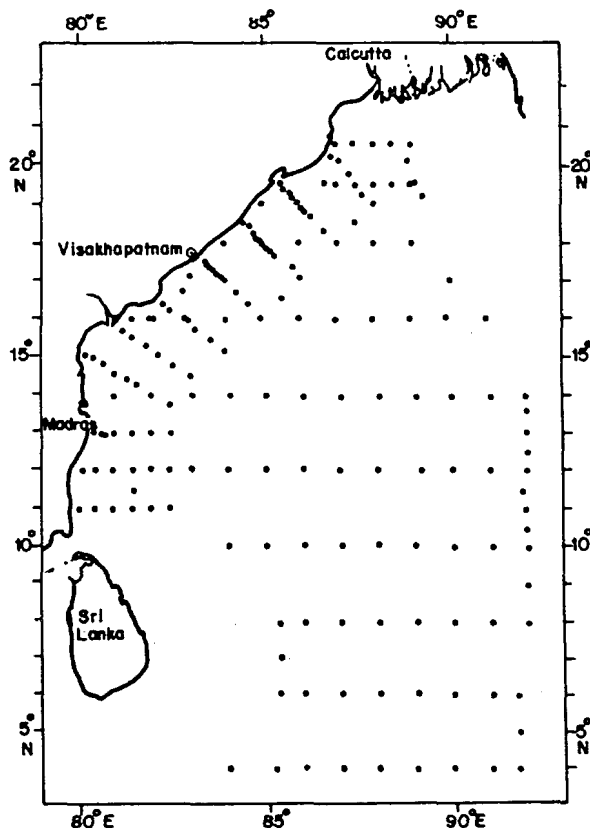


Fig. 1 - Station locations where wind observations were made during the cruise period (July-October 1984)

*Present address: PES College of Arts and Science, Farmagudi, Goa 403 405, India

conventional anemometry on board *ORV Sagar Kanya*⁵ were utilized to derive the wind stress distribution. The observation carried out from north to south during which the condition prevailed over the Bay of Bengal fairly represented the southwest monsoon period.

The aerodynamic relation used to compute the wind stress (τ) is

$$\tau = \rho_a C_D |V|^2$$

where ρ_a is density of air (1.175 kg.m^{-3}), C_D drag coefficient and $|V|$ the magnitude of wind velocity. In the present study a variable C_D has been applied following Hsue⁶.

$$C_D = (0.46 + 0.14 V) \cdot 10^{-3} \quad \text{for } V < 15 \text{ m.sec}^{-1}$$

$$C_D = 2.63 \cdot 10^{-3} \quad \text{for } V > 15 \text{ m.sec}^{-1}$$

The computation provides τ values at the station locations for the observed wind field. From this the individual wind components τ_x and τ_y are computed using

$$\tau_x = |\tau| \sin \theta$$

$$\tau_y = |\tau| \cos \theta$$

where θ is direction of wind with respect to true north. Giving weightage to the number of observations (n) available in each one degree square grid, the mean components $\bar{\tau}_x$ and $\bar{\tau}_y$ are computed from the following equations.

$$\bar{\tau}_x = \frac{1}{n} \sum_{i=1}^n \tau_{xi}$$

$$\bar{\tau}_y = \frac{1}{n} \sum_{i=1}^n \tau_{yi}$$

The mean direction θ is computed using

$$\theta = \tan^{-1} \left[\frac{\bar{\tau}_x}{\bar{\tau}_y} \right]$$

The wind stress is considered to be acting in the direction of the wind itself. Westerly winds give rise to eastward directed stress (τ_x) and southerly winds, the northward directed stress (τ_y).

In order to have a reasonable resolution in the computation of the wind stress curl, an area of 1° square is selected as higher grid size leads to underestimation of the curl value⁷. The vertical component of curl is computed from the relation,

$$\hat{k} \cdot \nabla \times \tau = \frac{\partial \bar{\tau}_y}{\partial x} - \frac{\partial \bar{\tau}_x}{\partial y}$$

where k the unit vector along the Z-axis and ∇ is the operator.

Results and Discussion

Wind system over the Bay of Bengal—The southwest monsoon period of 1984 was characterised by the presence of severe cyclonic activity over the Bay of Bengal⁸ and characterised by the presence of irregular wind system compared to the mean winds (Fig. 2). The observations show an inconsistent wind distribution over north of 15°N . Near the head of the Bay of Bengal when the winds are from east, northeasterlies can be seen over the eastern half of the Bay between 14° and 15°N . The southern and the western regions also show irregular wind fields with southerlies, southwesterlies and northwesterlies. Another conspicuous feature is the presence of high wind-stress components $\bar{\tau}_x$ and $\bar{\tau}_y$ (0.25 and 0.20 N m^{-2} respectively) in the northern Bay of Bengal between 15° and 16°N lat. and 85°E long. Incidentally, the $\bar{\tau}_x$ distribution derived from climatological mean wind field¹⁴ shows a $\bar{\tau}_x$ maximum (0.22 N m^{-2}) at $15^\circ 30'\text{N}$ lat. and $85^\circ 30'\text{E}$ long. and the observed wind also shows $\bar{\tau}_x$ and $\bar{\tau}_y$ with magnitudes 0.20 N m^{-2} around 16° and 17°N and 86°E (Fig. 3a and b). This feature gives a satisfactory comparison with the climatological wind stress and the observed wind stress during the southwest monsoon period. Further, it suggests that as observed wind field compares fairly well

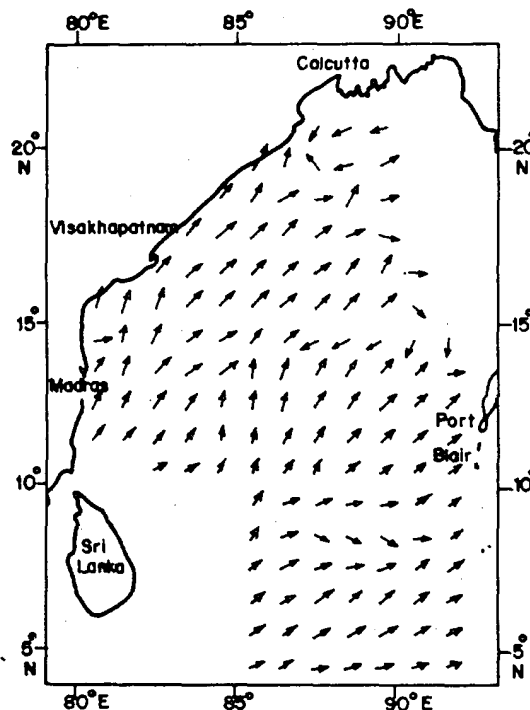


Fig. 2 — Mean wind direction derived from observed wind data

with the climatological mean wind field, it can be used to compute wind stress and wind stress curl.

The negative component of $\bar{\tau}_x$ in the northern region of the Bay of Bengal is due to the mon-

soon depressions and the associated easterly winds. Earlier studies also have reported negative wind stress component in the vicinity of this area during the southwest monsoon season⁹.

The $\bar{\tau}_x$ distribution when examined in a direction normal to the coast line exhibits a wavy pattern with 2 regions of maximum values (0.20 N m^{-2}) on the northwest and southeast with a low ($< 0.05 \text{ N m}^{-2}$) in the central Bay of Bengal (Fig. 3a). These maxima may be associated with the Bay of Bengal and Arabian Sea branches of the southwest monsoon¹⁰ respectively. The Bay of Bengal branch enters the Bay of Bengal across the southern boundary and the $\bar{\tau}_x$ values associated with this branch attain noticeable magnitude (0.25 N m^{-2}) in the southeastern Bay of Bengal which extends up to 13°N lat. The cross equatorial flow becomes weak around peninsular India and intensifies ($\bar{\tau}_x$ about 0.25 N m^{-2}) as it enters the Bay of Bengal across the southern boundary. Cadet and Reverdin¹¹ attributed these maxima to the pressure gradient existing over the Arabian Sea. North of this latitude, the occurrence of the second maximum (0.20 N m^{-2}) may be associated with the intensification of the low level air flow of the Arabian Sea branch over the Bay of Bengal¹². It may be worthwhile to note that the southern region shows an increase in the $\bar{\tau}_x$ (0.25 N m^{-2}) than the northern region where $\bar{\tau}_x$ is 0.20 N m^{-2} (Fig.3b).

Wind stress curl over the Bay of Bengal—The vertical component of wind stress curl computed from $\bar{\tau}_x$ and $\bar{\tau}_y$ fields is given in the Fig. 4. The Bay of Bengal branch of the southwest monsoon, after entering the Bay of Bengal, strengthens and gives rise to an increase in the wind stress curl. This increase can be seen along 86°E meridian while low magnitudes occur towards the east (91°E) as well as west (82°E), indicating the presence of the strong air flow from the Bay of Bengal branch of the southwest monsoon (Fig. 4). The central Bay of Bengal shows high negative curl τ regions with values ranging from -8 to -10 (10^{-7} N m^{-3}) occupying large area around 15°N . The northern and southern regions show positive curl τ fields ($8.10^{-7} \text{ N m}^{-3}$). These regions extend towards the central and eastern parts and are oriented approximately in a southwest-northeast direction. Another negative curl region is present in the southeastern Bay of Bengal with a magnitude of $-2.10^{-7} \text{ N m}^{-3}$.

The studies of Hantel¹³ on the distribution of curl τ also have shown similar results in the Bay of Bengal region. Though the patterns of negative and positive curl fields have a one to one corre-

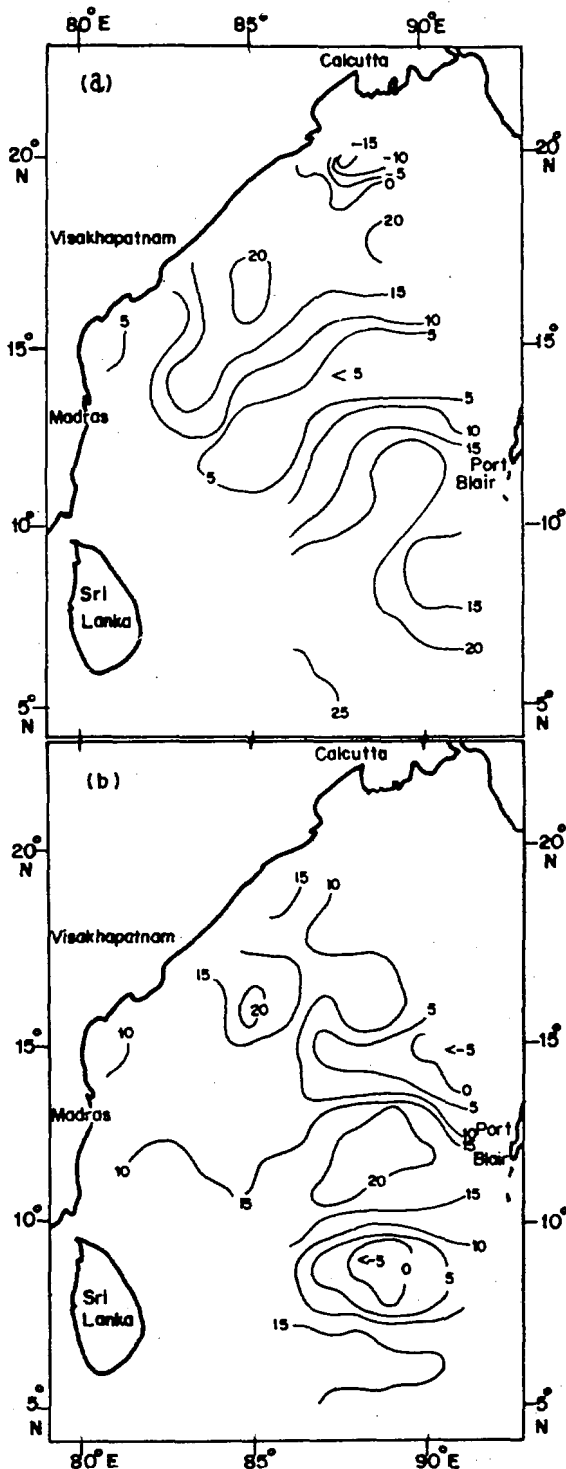


Fig. 3—Distribution of mean wind component ($\times 10^{-2} \text{ Nm}^{-2}$) (a) $\bar{\tau}_x$ and (b) $\bar{\tau}_y$

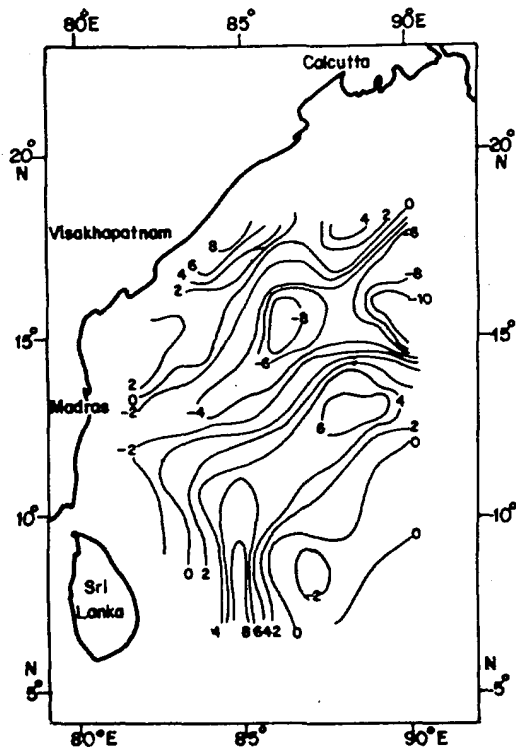


Fig. 4 – Distribution of wind stress curl (10^{-7} Nm^{-3})

spondence with the present study, the magnitudes obtained by Hantel¹³ are on the lower side. This can be due to the selection of C_D values by Hantel¹³ which range from 1.20×10^{-3} to 1.60×10^{-3} and the wind data are for 2° square grid. Whereas in the present study, the C_D values used (given in Materials and Methods) are on the higher side as the wind data are taken from the atlas of Hastenrath and Lamb¹⁴ for 1° square grid. The comparison between the curl τ based on these 2 computations provides close correspondence inspite of different C_D values.

Vertical velocity field – An important application of the curl τ is the determination of vertical velocity in the upper wind-influenced layer¹⁵. The Ekman divergence of the surface layer drives the water below in order to conserve the continuity of volume. Therefore, the curl τ provides comparatively reasonable values of vertical velocity at the base of the Ekman layer. The values of curl τ obtained at the centre of each 1° square grid have been used to compute the vertical velocity at the base of the surface Ekman layer. The vertical velocity (w_E) is assumed to be zero at the surface and bottom, i.e.,

$$w_E = 0, z(0, -h)$$

Applying this boundary condition in the following relation¹⁵, w_E is calculated

$$w_E = \frac{1}{\rho f} \text{curl } \tau$$

where f is the Coriolis force and ρ the mean density of the surface layer.

As seen from the curl τ field, the vertical velocity field also shows alternate regions of positive and negative (upward and downward) velocity distribution (Fig. 5). The central Bay of Bengal shows high velocity values ranging from -10 to -25 ($10^{-6} \text{ m.sec}^{-1}$) occupying a zonal belt from 87° to 90°E , along 15°N . The northern and southern regions show large diverging areas (15 to $20 \times 10^{-6} \text{ m.sec}^{-1}$) associated with the wind stress maxima present in these 2 regions. A recent analysis of the thermal structure of the upper layer in this region⁵ shows rising of the isotherms agreeing with the upwelling of the order of $20 \times 10^{-6} \text{ m.sec}^{-1}$. The divergence in the southern region of the Bay of Bengal extends towards the central and eastern parts. Another negative vertical velocity region is present in the southeastern Bay of Bengal with magnitude $5 \times 10^{-6} \text{ m.sec}^{-1}$.

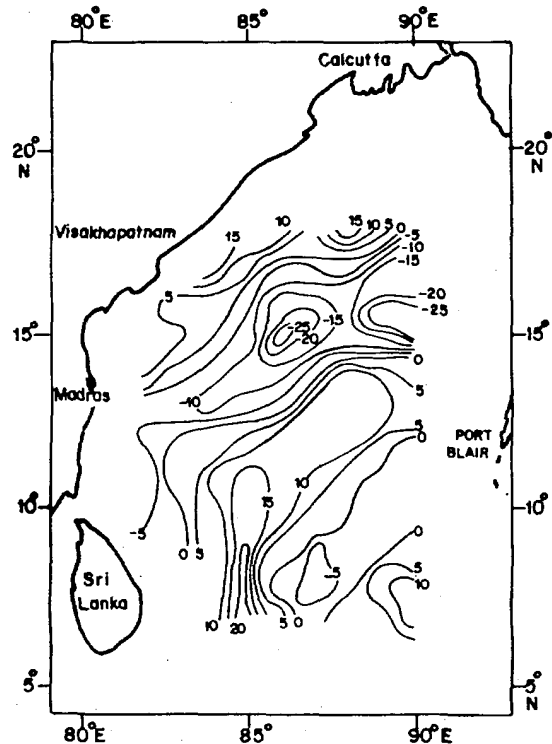


Fig. 5 – Vertical velocity field, w_E (10^{-6} m s^{-1})

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