

## POTENTIAL VORTICITY FIELD IN THE BAY OF BENGAL DURING SOUTHWEST MONSOON

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### ABSTRACT

The distribution of potential vorticity along potential density surfaces in the upper 500 m indicates the presence of a wind driven anticyclonic gyre between 10°N and 14°N in the eastern Bay during southwest monsoon. The vertical extent of the wind influence increases from around 200 m in the southern Bay to over 500 m in the central Bay. The effect of freshwater discharge is confined to the shallow depths in the northern parts of the Bay. On the shallower isopycnals (<26.9  $\sigma_\theta$ ), potential vorticity distribution is complex due to wind and freshwater forcings. The  $\beta$ -effect dominates the potential vorticity field on 26.9  $\sigma_\theta$  isopycnal. The field of potential vorticity closely follows that of circulation.

### INTRODUCTION

Potential vorticity is a good indicator of large scale ocean circulation (Stramma, 1984 a&b) and has been used as a tracer for the convectively formed watermasses (Talley and McCartney, 1982). It is a fundamental dynamic quantity in the theories of large- scale wind-driven ocean circulation (Rhines and Young, 1982; Young and Rhines, 1982; Luyten et al, 1983). The distribution of potential vorticity on the potential density surfaces has been studied in the Atlantic Ocean (McDowell et al, 1982), Pacific Ocean (Talley, 1988) and the world oceans (McCartney, 1982 and Kef-fer, 1985). Somayajulu et al (1987) presented sections of potential vorticity in the Bay of Bengal during pre-monsoon and post-monsoon periods. In all the above studies, the relative vorticity has been neglected compared to planetary vorticity,  $f$  ( $=2\omega \sin \phi$ , where  $\omega$  is the angular velocity of the earth's rotation and  $\phi$  is the latitude), at scales larger than the Rossby radius of deformation (50-100 km). This leads one to determine the potential vorticity ( $q$ ) assuming quasi-geostrophic baroclinic ocean (Holland et al, 1984 and Rhines, 1986) from the hydrographic measurements of density.

In this paper, the distribution of 'q' along select potential density surfaces in the upper 500 m of water column in the Bay of Bengal has been presented for southwest monsoon period and discussed in relation to the freshwater discharge, wind forcing and circulation.

### DATA AND METHOD

The hydrographic data collected onboard 'ORV *Sagar Kanya*' using a CTD profiler in the open-sea area of the Bay of Bengal along 9 zonal sections, extending from 4N to the head of the Bay during southwest monsoon period (August-September)

of 1984 were utilised. The CTD temperature and salinity data at each station, obtained nearly at 2.5 db interval, were used to compute the potential density. The corresponding depths of the isopycnal surfaces were read out. The upper 500 m water column was divided into thin isopycnal layers at  $0.5 \sigma_\theta$  interval. For isopycnals higher than  $22.5 \sigma_\theta$  the interval is  $0.2 \sigma_\theta$ . Each isopycnal layer is represented by the mean potential density surface (Table 1). The topography of these isopycnal layers varies from one location to the other in the Bay and the depths presented in Column 3 of Table 1 represent the extreme values on either side.

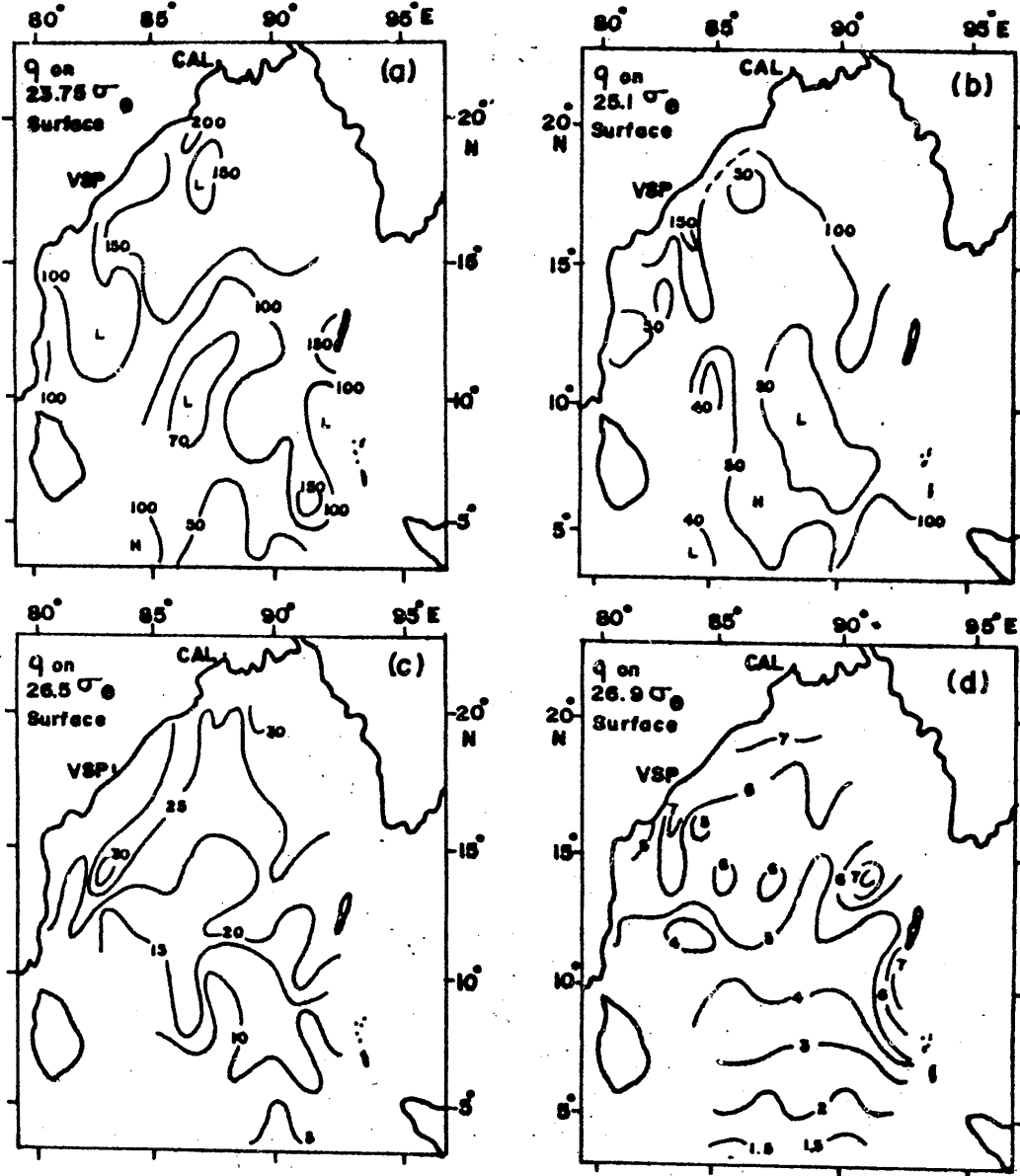


Fig. 1. Potential vorticity along potential density surfaces (a) 23.75, (b) 25.1, (c) 26.5 & (d) 26.9

Potential vorticity ( $q$ ) was computed for each of the isopycnal layer, following McDowell et al (1982)

$$q = f \cdot (\partial \sigma_\theta / \partial p)$$

where  $\sigma_\theta$  is the potential density of the isopycnal surface referred to sea surface pressure (0 db) and  $\partial p$  is the thickness of the isopycnal layer in decibars. The potential vorticity is expressed as  $10^{-11} \text{ m}^{-1} \text{ s}^{-1}$ .

## RESULTS AND DISCUSSION

On 23.8 isopycnal (Fig. 1a), potential vorticity varies between 200 in the northwestern region and 50 in the southern Bay. It decreases southward along the western boundary from the head of the Bay to  $15^\circ\text{N}$ . South of it, the potential vorticity is around 100 along the western boundary. A large cell of high potential vorticity (150) occurs north of  $15^\circ\text{N}$  from  $90^\circ\text{E}$  to the western boundary. A closed cell of low (<70) potential vorticity appears between  $85^\circ\text{E}$  and  $87^\circ\text{E}$  in the zonal belt  $9^\circ\text{N}$ - $13^\circ\text{N}$  with the isotropes (lines of equal potential vorticity) oriented in a southwest-northeast direction.

On 25.1 isopycnal (Fig. 1b), the cell of high (150) potential vorticity persists at  $16^\circ\text{N}$  and  $83^\circ\text{E}$  and the isotrope 100 shifts northeastward. The low 'q' in the southern Bay as observed on the upper density surface is shifted westward and a closed cell of low (<50) potential vorticity is formed in the eastern Bay between  $6^\circ\text{N}$  and  $12^\circ\text{N}$ .

On 26.5 isopycnal (Fig. 1c), a tongue of low (<15) potential vorticity spreads north-eastward between  $10^\circ\text{N}$  and  $16^\circ\text{N}$  while a tongue of high (>20) spreads equatorward in the eastern Bay.

On 26.9 isopycnal (Fig. 1d), the isotropes are parallel to the latitudes in the region south of  $12^\circ\text{N}$ . A cell of low (4) potential vorticity appears between  $84^\circ\text{E}$  and  $85^\circ\text{E}$  along  $12^\circ\text{N}$ . North of  $14^\circ\text{N}$ , potential vorticity varies between 6 and 7.

During southwest monsoon, the wind forcing over the Bay is strong. This is compounded by the freshwater discharge along shoreward boundary of the Bay. Potential vorticity maxima result from the Ekman divergence and buoyancy flux transfer due to excess precipitation and run-off. Consequent to the freshwater discharge into the Bay, large vertical gradients in salinity and hence in density occur in the upper layers which in turn give rise to higher potential vorticity. The higher values (>150) of 'q' on the shallow isopycnal (23.8) result from the overlying low salinity waters in the northern Bay and west of the Andaman Islands since this isopycnal lies close to the sea surface (Table 1). As density increases the area of high 'q' is reduced and pockets of high potential vorticity with decreasing magnitude are confined to the northern Bay. This indicates the decreasing influence of the freshwater

Table 1. Isopycnal ( $\sigma_\theta$ ) layers and depth limits

Isopycnal layers	Mean-density surface	depth (m) limits
23.5-24.0	23.8	50-110
25.0-25.2	25.1	100-165
26.4-26.6	26.5	180-300
26.8-27.0	26.9	330-450

discharge with increasing depth. The lower (50) values of 'q', on the other hand, are noticed in the south Bay on this isopycnal which could be attributed to the advection of relatively saline and hence denser waters from the equatorial regions of the Arabian Sea. Since the cells of high and low 'q' are associated with cyclonic and anticyclonic gyres respectively, the cell of low 'q' on 23.8 isopycnal over the central Bay indicates the anticyclonic gyre at the depth range of this density surface. The circulation derived from the hydrographic data shows anticyclonic gyre in the central Bay at 50 m and 100 m depth levels, coinciding with the cell of low 'q' on 23.8.

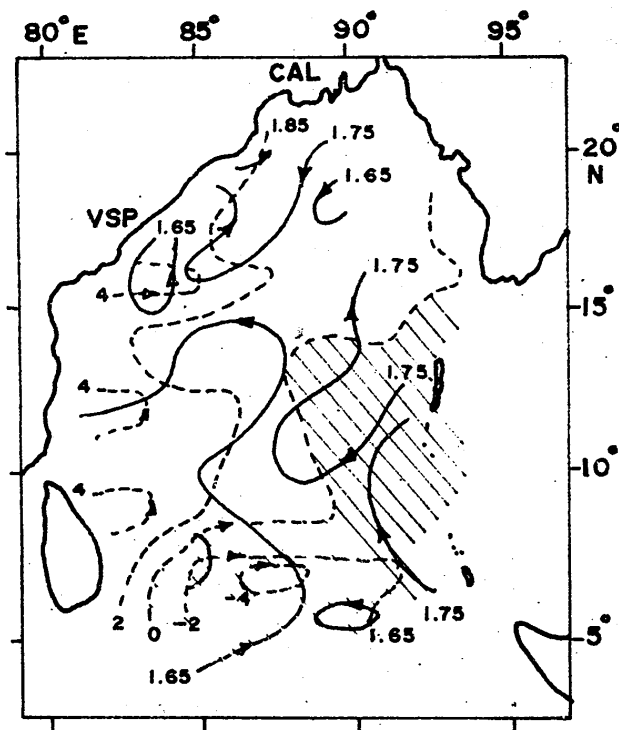


Fig.2. Dynamic topography at sea surface relative to 1000 db (—) & volume transport ( $10^6 \text{m}^3/\text{s}$ ) streamlines (- - -) for September (shaded region indicates southward transport).

An examination of the wind stress curl field for September in the Bay (Babu, 1987) shows negative wind stress curl in the eastern Bay and positive curl in the central regions. The associated Sverdrup volume transport is southward in the eastern Bay and northward in the western part of the Bay separated by the zero-line of transport, oriented in a southwest-northeast direction, over the central Bay (Fig. 2). Superimposed on this, is the dynamic topography at the sea surface relative to 1000 db surface during southwest monsoon which shows the northeastward flow in the central Bay with anticyclonic circulation on the east and cyclonic circulation on the west. This northeastward flow coincides with the zero-line of transport. Also, the isotrophes on 23.8 isopycnal over the central Bay are oriented in a southwest-northeast direction. This suggests that the anticyclonic gyre is due to the anticyclonic wind stress curl and vice versa. This signifies that anticyclonic circulation in the eastern and central regions of the Bay at the surface and deeper depths is due to wind forcing.

On the isopycnals shallower than 26.9 density surface, the isotrophes are distorted much from the latitudes. This indicates the complicated structure of density influenced by both freshwater discharge and wind forcing.

The tongue of low (<15) potential vorticity on 26.5 and the cell of low (4) potential vorticity on 26.9 coincide with the centre of the anticyclonic gyre on the dynamic topography maps at 200 m and 500 m depth levels respectively indicating that the wind influence penetrates upto greater depths in the central Bay. The centre of the anticyclonic gyre shifts towards northwest with depth.

The meridional gradient of potential vorticity ( $\partial q/\partial y$ ) is equal to  $\beta$  ( $= \partial f/\partial y$ , the meridional gradient of Coriolis parameter) south of 8°N on 26.5 and south of 14°N on 26.9 surfaces. This indicates weak forcing at these density surfaces according to the theory of Young and Rhines (1982). This suggests that the vertical extent of wind forcing is limited to shallower depths (around 200 m) in the southern Bay and increases to over 500 m in the central Bay.

### CONCLUSIONS

It is found that the vertical extent of the influence of freshwater discharge is limited to the depths of upper 100 m in the northern regions of the Bay and that of wind forcing, on the other hand, increases from 200 m in the south to over 500 m in the central Bay. The circulation derived from the hydrographic data assuming a zero-horizontal velocity at 1000 m (reference level) is in good agreement with the distribution of potential vorticity which is independent of reference level.

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