

## COASTAL CIRCULATION AND UPWELLING INDEX ALONG THE EAST COAST OF INDIA

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### ABSTRACT

Hydrographic data collected during November - December, 1983 and July-August (1984) along sections normal to the east coast of India were analysed for salinity and temperature structures. Coastal circulation and volume transports were derived using 500 db surface as a reference level. The dynamic topography charts show strong southwesterly flow with a large cyclonic cell during NE monsoon. The dynamic topography charts during SW monsoon show a complicated pattern with cyclonic and anti-cyclonic cells along the coast. From the Upwelling Index derived from the winds obtained from the IDWRs (Indian Daily Weather Reports) the entire coast is divided into three zones, characterised by (i) negative index in the northern zone (ii) both positive and negative indices of less magnitudes in the central zone and (iii) higher indices (both positive and negative) in the southern zone.

### INTRODUCTION

The east coast of India is influenced by two reversable monsoons, SW and NE. The SW monsoon prevails from June to September with steady and strong southwest winds blowing at a speed of about 10- 15 m/s. The NE monsoon prevails from November to February with weak winds of 5-7 m/s speed. Along the coast fresh-water (of 2300 km<sup>3</sup>) is discharged into the Bay through the major rivers - Godavari, Krishna, Mahanadi and Cauvery. Freshwater discharge dilutes the sea water in the upper layers, thereby, developing strong salinity gradients. The reversable winds drive the surface circulation and change the circulation twice an year. The coupled driving forces of winds and freshwater made the circulation complicated.

Vertical motions leading to upwelling and sinking were examined by many researchers (La Fond, 1954; Ramasastry and Balarama Murty, 1957 and Varadachari, 1958). The dynamic topography charts for the Bay of Bengal (Duing, 1970 and Wyrski, 1971) show a northerly current along the east coast of India with a clockwise cell in the north central Bay. Duing's (1970) chart indicates a southerly meridional flow further east of this cell which merges finally with the north equatorial current in the south Bay. A complex pattern with the formation of several cells in the surface circulation was observed by Rao (1977).

The above studies do not contribute to the entire coastal belt of the east coast of India but are limited to certain pockets while some pertain to the open-sea areas. It is in this context that the present paper is aimed at to describe the coastal circulation for NE and SW monsoon periods along the east coast of India and the monthly Upwelling Index.

## DATA AND METHODS

Hydrographic data collected during November/December, 1983 onboard RV *Gaveshani* through conventional hydro-cast and CTD data during July/August, 1984 onboard ORV *Sagar Kanya* were used in this study. The sections were normal to the coast from the Head of the Bay to 10°N in the the south. The dynamic computations were carried out with reference to 500 db to derive the geostrophic flow field and volume transport computations. For stations shallower than reference level, the flow field has been derived by adopting the method suggested by Fomin (1964).

Synoptic wind data for five years from 1980 to 1984, obtained from IDWRs at eight stations - namely Balasore, Gopalpur, Visakhapatnam, Kakinada, Machilipatnam, Nellore, Madras and Cuddalore were used for computing the Upwelling Index (Hart & Currie, 1960; Bakum, 1973 and Royer, 1981) using the formula

$$M_x = t_y/f$$

where  $t_y$  is the wind stress component in dyne/cm<sup>2</sup> in y-direction  
f is coriolis parameter

## RESULTS AND DISCUSSION

The geostrophic circulation has been derived for northeast and southwest seasons taking 500 db surface as reference level and the dynamic topography charts for NE & SW monsoons at sea surface, 100 db, 200 db and 400 db surface are shown in Figs. 1 and 2 respectively.

During NE monsoon (Fig. 1), the flow at the surface is towards southwest and parallel to the shore. A large cyclonic gyre extends towards south from 15°N to 13°N. Very near the coast and in the vicinity of Godavari and Krishna river mouths and off Visakhapatnam, the circulation is anti-cyclonic. Along the shelf, north of Visakhapatnam and upto the head of the Bay flow is northeasterly. Off Madras, along 13°N, the flow is offshore. The circulation pattern at 100 db surface is similar to that of the surface circulation. At 200 db surface a large cyclonic cell is observed extending from the head of the Bay to 12°N. However, at 400 db surface, there is a noticeable change in the circulation pattern. A small cyclonic cell centred around 14°N and 81°E is observed. In the northern bay, the flow is towards coast. The flow is nearly in southwesterly direction along the coast.

During SW monsoon (Fig. 2), the surface circulation is very complicated. There are cyclonic and anti-cyclonic eddies situated north of Visakhapatnam between 19°N and 17°N and between 16° and 15°N off Godavari and Krishna rivers. One more cyclonic cell exists south of Madras from 13° to 11°N and 80° and 82°E. At the head of the Bay, the flow is southwesterly with an offshore component. Along 14°N, the westward flow is divided into two branches (i) northerly and (ii) southerly. South of Madras around 82°E, an anti-cyclonic eddy with weak flow is noticed. Varadachari, Murty and Das (1968) also reported the same anti-cyclonic gyres in the month of June. At 100 db surface, the flow more or less resembles that at the surface. The anti-cyclonic cell around 15°N weakens and becomes very small. The

cyclonic eddy south of Madras observed on the surface extends a little north upto around 14°N. North of Chilaka lake, the flow is offshore with a southeasterly component. At 200 db surface, at 20°N, the flow is towards onshore. The cyclonic and anti-cyclonic eddies are still observed along the coast at this level also. At 400 db surface, most of the eddies disappeared except one, the cyclonic eddy along 18°N

**Volume transport:**

The geostrophic volume transport in the upper 500 m is towards south with a magnitude variation from  $0.68 \times 10^6 \text{ cm}^3 \text{ sec}^{-1}$  at the head of the Bay to  $14.7 \times 10^6$

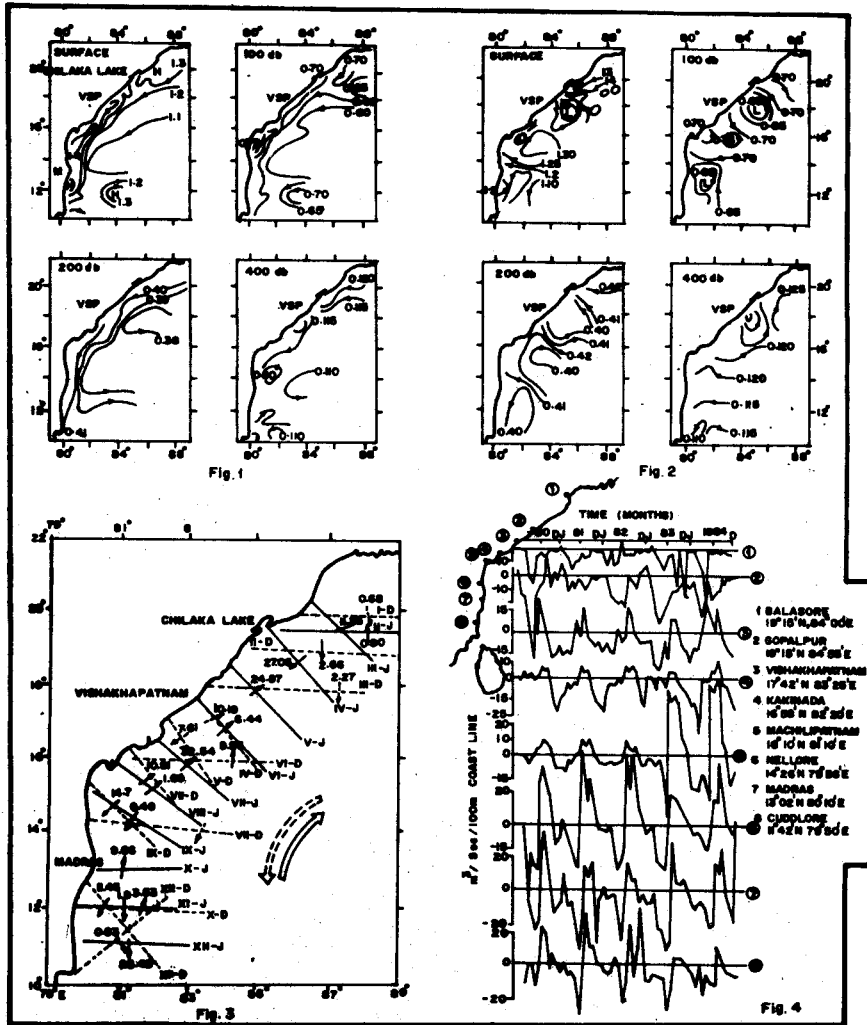


Fig.1. Dynamic topography at surface, 100 db, 200 db and 400 db during NE - Monsoon.  
 Fig.2. Dynamic topography at surface, 100 db, 200 db and 400 db during SW - Monsoon.  
 Fig.3. Net transport ( $10^6 \text{ cm}^3 \text{ Sec}^{-1}$ ) across each of the sections during NE(- ->) and SW (—>) Monsoon.  
 Fig.4. Upwelling Index (onshore - offshore Ekman transport) ( $\text{M}^3/\text{Sec}/100\text{m}$  coastline) from the eight coastal stations from 1980-1984.

$\text{cm}^3\text{sec}^{-1}$  between  $14^\circ$  and  $15^\circ\text{N}$  during northeast monsoon (dashed line in Fig. 3). During SW monsoon, the transport is more orderly. North of  $15^\circ\text{N}$  it is almost towards northeast upto  $18^\circ\text{N}$ . Below  $15^\circ\text{N}$  the transport is southward. It varies from  $0.49\text{ Sv}$  around  $14^\circ\text{N}$  to  $32.5$  around  $16^\circ\text{N}$  lat. The total volume transport in the study area is about  $13 \times 10^6 \text{ cm}^3\text{sec}^{-1}$  towards south during northeast monsoon while it is  $12 \times 10^6 \text{ cm}^3\text{sec}^{-1}$  directed northwards during southwest monsoon. On the whole, one realises a near balance in the computed transports, though, the flow during the northeast monsoon, marginally exceeds the flow during SW monsoon.

#### *Upwelling Index:*

The magnitude of the offshore component of the Ekman transport is considered as an indicator of the amount of water upwelled through the bottom of the Ekman layer replacing those driven offshore. This is termed as Upwelling Index (Hart & Currie, 1960; Bakum, 1973 and Royer, 1981).

Earlier investigators (La Fond, 1954; Balarama Murty, 1958; Varadachari, 1958 and 1961; Murty and Varadachari, 1968 and Gopalkrishna and Sastry, 1985) reported upwelling at various locations along this coast during pre- and SW monsoon seasons. These have been referred to in relation to the derived flow field from thermo-haline structures confined to the shelf areas. An attempt is made to compute the upwelling Index at the eight coastal stations (Fig. 4).

The Upwelling Index at Balasore is mostly negative throughout the year. At Gopalpur, the period from January through April could be considered as the period of negative upwelling. From April to August occasional intense upwelling process could be seen. The Upwelling Index values show well defined cyclicality at Visakhapatnam. Compared to the earlier two stations the trend is more regular with improved magnitudes of  $15 \text{ m}^3/\text{sec}/100 \text{ m}$  coast line. Upwelling Index at Kakinada closely resembles that at Visakhapatnam with low positive Upwelling Index compared to that of at Visakhapatnam. The values of Upwelling Index show periodic change from positive upwelling to that of negative along Machilipatnam coast. The values of Upwelling Index at Nellore are very high ( $25 \text{ m}^3/\text{sec}/100 \text{ m}$  coast line) compared to that at other regions along the coast. The distribution of Upwelling Index values at Madras closely resembles that of at Nellore with less magnitudes ( $20 \text{ m}^3/\text{sec}/100 \text{ m}$  coast line). The Upwelling Index at Cuddalore shows the similarity with that of at Madras.

Following the distribution pattern of Upwelling Index along the coast (Fig. 4), the entire region can be divided into three zones viz., northern, central and southern. In the northern zone comprising - stations at Balasore, Gopalpur and Visakhapatnam the Upwelling Index is predominantly negative except at Visakhapatnam, where positive Index is seen from July to September. In the central zone (Kakinada and Machilipatnam) the magnitudes of Upwelling Index are low compared to those at the other regions along the coast. In this zone, the intensity of positive and negative indices are found to be equally distributed. In the southern zone (Nellore, Madras and Cuddalore) high values of Upwelling Index are noticed compared to other northerly zones with fluctuations in the Upwelling Index. These indices clear-

ly showed sinking predominant in the northern zone in the course of an year. In the central zone, however, prevailing upwelling (Varadachari, 1958 & Murty and Varadachari, 1968) is well supported by the Upwelling Index.

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