

# CURRENTS OFF BOMBAY DURING FEBRUARY, 1976

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## ABSTRACT

Current measurements at two stations off Bombay showed that the tidal currents were strong farther from the shore. Residual currents had a northerly flow near the shore while there was a weak southerly flow away from the shore. An examination of probable Ekman drift showed that its effect was either negligible or was masked by other current constituents. Temperature and salinity did not show much variation. Temperature away from the shore was slightly lower than that near the shore while salinity at the offshore station was slightly higher. The possible reasons for the variability of the currents are discussed.

## INTRODUCTION

The study of currents is important for a better understanding of the flow of waters of the continental shelf. Such a study facilitates the exploration of oil and gas and the control of sewage and other pollutants discharged into the sea. The currents largely determine the dilution and residence time of pollutants. The study of currents is particularly important off Bombay because a large amount of sewage and industrial wastes are discharged into the sea.

Off Bombay, the continental shelf is wide extending upto 280 km from the shore. The shelf edge occurs at a depth of about 90 m. In such a wide shelf, the tides coupled with the winds can be a major current producing agent.

The general surface circulation in the Arabian Sea is counter clockwise during the NE monsoon. By February, this system gradually reverses into a clockwise circulation which intensifies during the SW monsoon. However, the periods of transition can vary depending on the variability of the monsoon systems.

Currents in the continental shelf are a combination of tidal currents, density currents, wind induced currents, currents due to surface and internal waves and those due to the land drainage. At present, very little information is available on the spatial and temporal structure of currents of this area. Current measurements reported for the area are scanty and are mainly restricted to surface currents, close to the shore (Josanto and Desai, 1975; Anonymous, 1971). However, reports on current measurements are available from 3 depths near the Angria Bank, beyond the continental shelf off Ratnagiri, about 200 km south of Bombay (Nair and Bhat-tathiri, 1968). Sastry and D'souza (1972) computed the Ekman drift for the surface and found that the results agreed with the trajectories of the surface floats released off Tarapur, at a point where the depth is 6 m. Recently NIO has carried out current measurements at 4 stations between Bombay High and Bombay harbour (Anonymous, 1976).

This paper presents the details of vertical structure of currents observed at

two stations off Bombay during February, 1976.

MATERIAL AND METHODS

In February, during the second cruise of R.V. *Gaveshani*; current measurements were made at two stations over one tidal cycle each (see Fig. 4). *Gaveshani* was anchored at each station for 13 hours. Station

1 was occupied from 1230 hrs on 24 February to 0030 hrs on 25 February and station 2 from 1800 hrs of 28 February to 0700 hrs of 29 February, 1976. The average depths at these stations were 33 and 50 m respectively. Station 1 was occupied during the time when the predicted tidal range at Appolo Bander was 2.08 m, while the observations at station 2 were during the time when the range

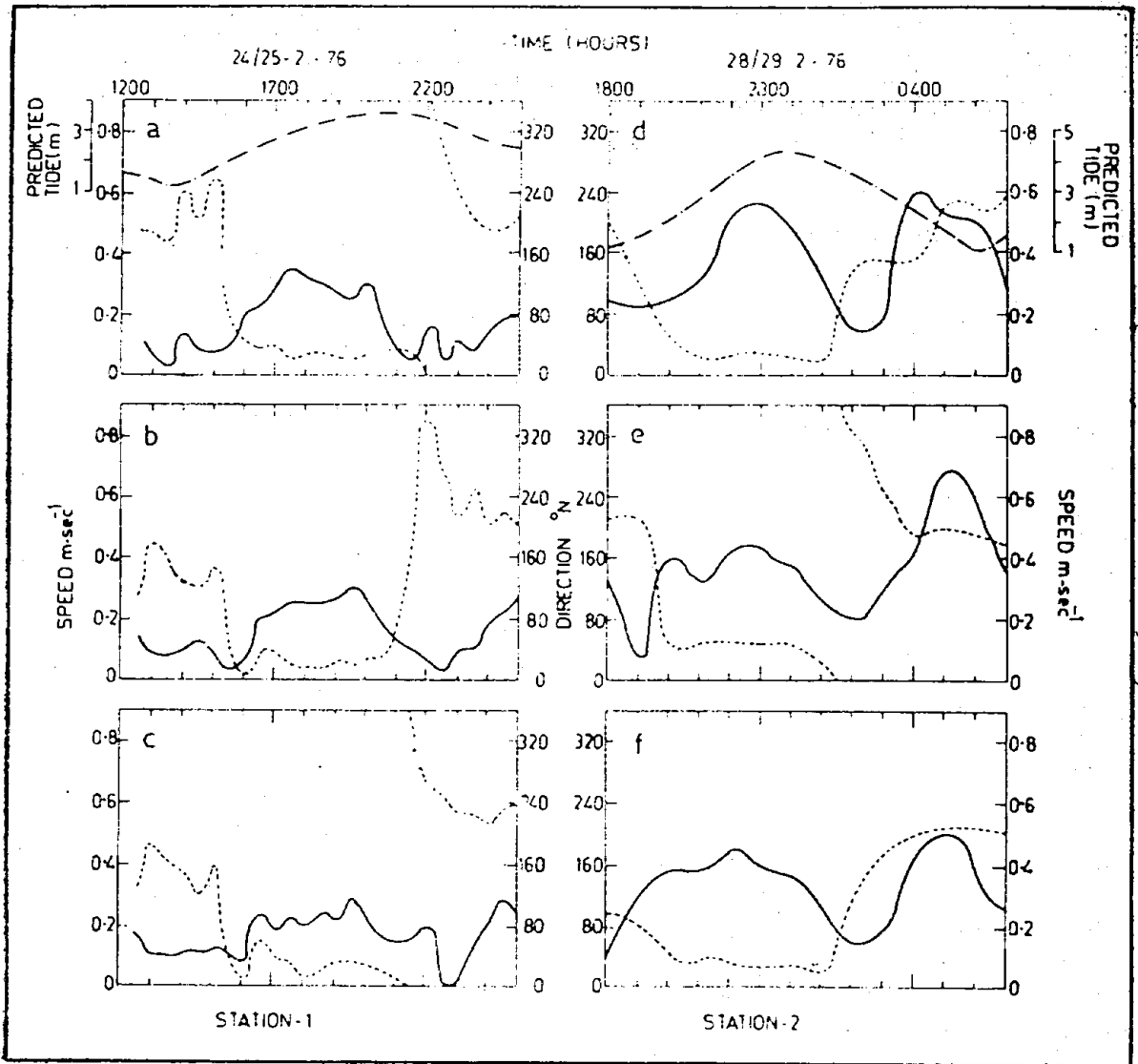


Fig. 1. Variation of current speed (—) and direction (-----) at 10, 25 and 30 m (a, b & c) at station 1 and 10, 30 and 40 m (d, e & f) at station 2 and the predicted tide at Appolo Bander (-.-.-).

## Currents off Bombay

was 3.09 m. Current speeds and directions were measured from surface to near bottom at every 5 m interval using a direct reading impeller type current meter of "Toho Dentan" make. Half hourly observations were made at station 1, while at station 2 measurements were restricted to one hourly interval. Wind speed and direction were noted simultaneously while the temperature and salinity of the water were measured periodically.

As the ship's presence is likely to distort the surface flow pattern, surface current measurements, though made, are not included in this paper. Individual current vectors were resolved into E-W and N-S components and the residual currents were computed from these.

### RESULTS

#### Tidal currents

*Station 1* : At 5 m depth flood direction was N to NE while that of ebb was S to SSW. Tidal currents were oscillatory and maximum speeds of  $0.25 \text{ m sec}^{-1}$  were observed during both flood and ebb.

Counter clockwise rotation of currents was observed with changing tidal phase at 10 m (Fig. 1a) and at 15 m. At these depths flood had a persistent direction of NNE and a maximum speed of  $0.35 \text{ m sec}^{-1}$ . The ebb direction was variable (SW to WSW) and the maximum speed was about  $0.2 \text{ m sec}^{-1}$ . The change in the direction from ebb to flood was slightly faster as compared to that from flood to ebb.

At 20 m the maximum speeds were the same as in the layer just above. At 20 and 25 m, flood was generally directed to NNE and the ebb direction was

variable. At 25 m, flood and ebb reached maximum speeds of  $0.3 \text{ m sec}^{-1}$ . Though the counter clockwise rotation of currents appeared to be present, it was not clearly defined. The transition from each phase of the tide was gradual (Fig. 1b).

Near the bottom, counter clockwise rotation of the currents with reduced speeds was observed (Fig. 1c). However, the semi-tidal fluctuations in the speeds of current observed in the upper layers were not well defined close to the bottom. Flood and ebb maxima were of the order of  $0.25 \text{ m sec}^{-1}$ .

*Station 2* : The tidal currents were oscillatory in the upper layers (5, 10, 15, and 20 m). Flood had a persistent direction NNE, while the ebb direction was variable, S to SSW (Fig. 1d). In the upper layers, maximum flood and ebb speeds were about  $0.55$  and  $0.60 \text{ m sec}^{-1}$  respectively. At 20 m depth, maximum speeds of ebb and flood were  $0.45 \text{ m sec}^{-1}$ .

Counter clockwise rotation of the tidal currents was observed at 30 m depth (Fig. 1e) and at 25 m depth. At 25 m, flood was directed to NNE and the ebb direction varied between SSW to WSW while at 30 m depth flood direction was NE and ebb direction was SW. Maximum flood and ebb currents at these depths were of the order of  $0.45$  and  $0.65 \text{ m sec}^{-1}$  respectively. Thus, associated with these rotary currents, were a decrease in the flood and a slight increase in the ebb velocities.

Below this, the oscillatory nature of the tidal currents was restored (35, 40 and 45 m). Flood was NE at all these depths and the direction of the ebb was SSW at 40 m (Fig. 1f) and at 35 m depths. The very high values of ebb

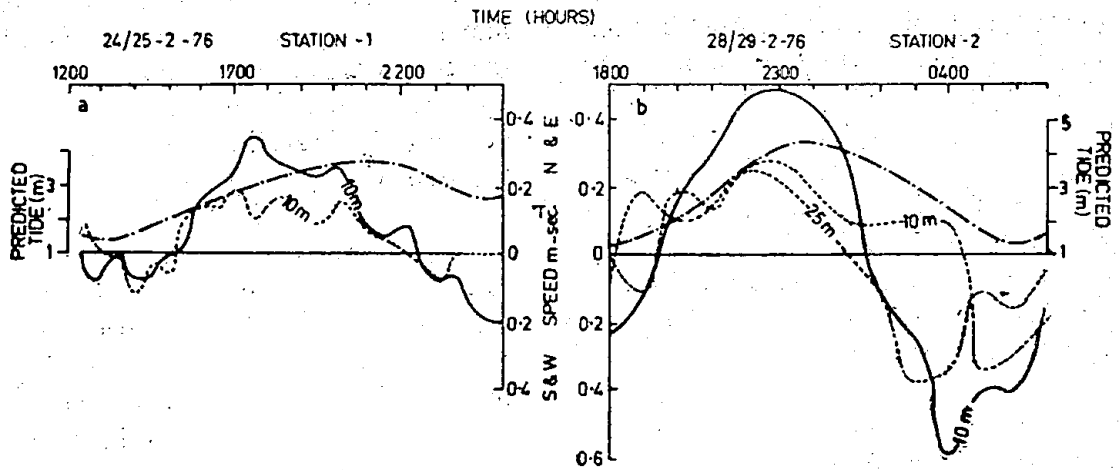


Fig. 2. Resolved components at 10 m Easterly (-----) and Northerly (——) and predicted tide at Appolo Bunder (-.-.-.-). Easterly component for 25 m is also shown for station 2.

observed at mid depths were found to decrease at lower layers, being of the order of 0.6, 0.5 and 0.45 m sec<sup>-1</sup> at 35, 40 and 45 m, respectively.

*U and V components*

At the station 1, the easterly components did not show clear periodicity with the tide—the flow being mainly easterly, but for slight reversals observed during the ebb (Fig. 2a). The maximum easterly and westerly speeds were 0.25 and 0.15 m sec<sup>-1</sup> respectively. At the station 2, the easterly flow associated with the flood and the westerly flow with the ebb reached the maximum values of 0.3 and 0.4 m sec<sup>-1</sup> respectively. While the easterly flow dominated the surface and bottom layers, the flow was periodic with the tides at mid-depth (Fig. 2b).

At the station 1, northerly component was periodic with the tide throughout

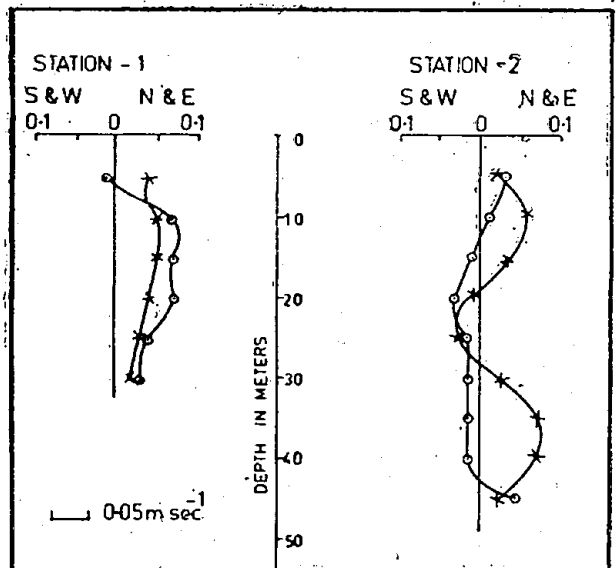


Fig. 3. Depthwise distribution of average components. Easterly (x—x) Northerly (o—o).

## Currents off Bombay

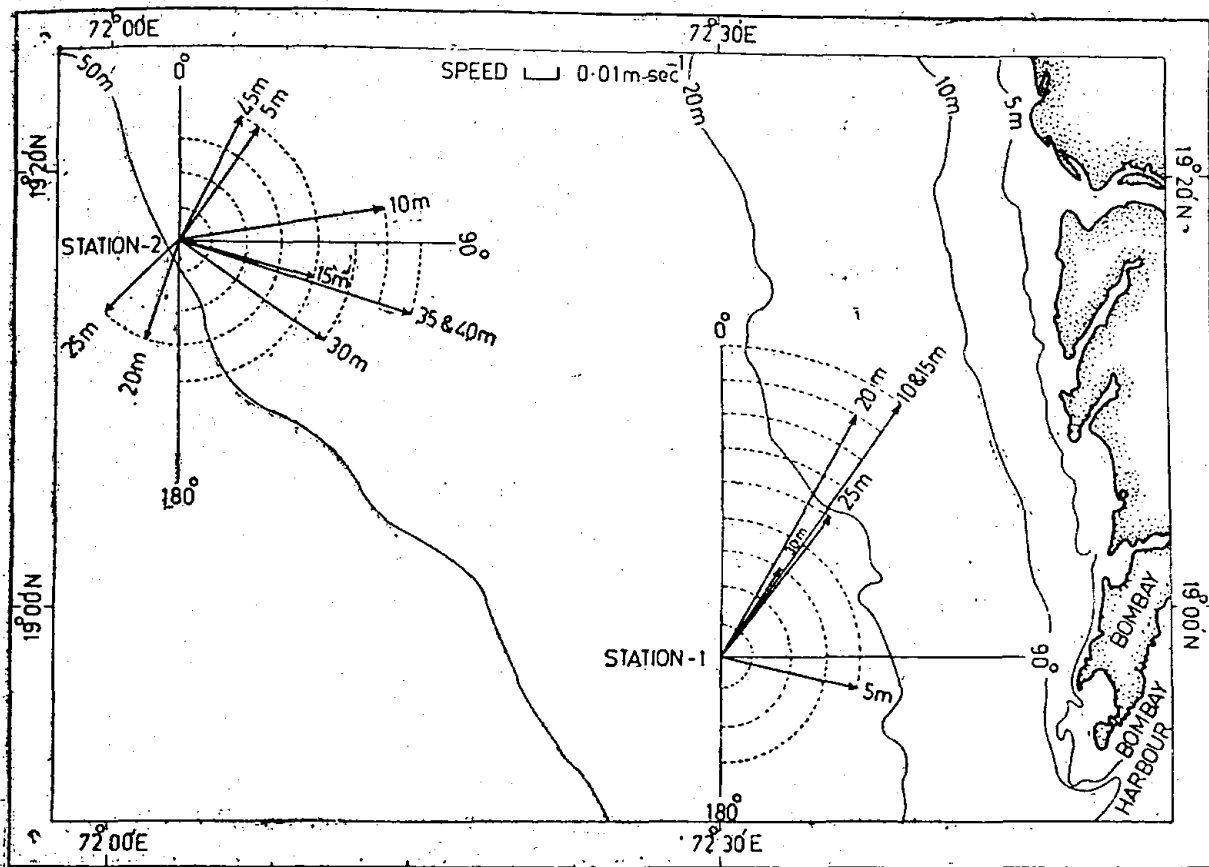


Fig. 4. Vertical structure of residual currents.

the water column. The flow was northerly during the flood and southerly during the ebb (Fig. 2a). A faster northerly flow was encountered at mid-depth and the maximum speed was  $0.35 \text{ m sec}^{-1}$ . The maximum flow in southerly direction was  $0.2 \text{ m sec}^{-1}$ . At the station 2 also, the northerly components were periodic with the tide (Fig. 2b). Southerly flow associated with the ebb was faster—the maximum speeds being  $0.65$  and  $0.5 \text{ m sec}^{-1}$  in southerly and northerly directions respectively.

Depthwise distribution of the average current components is shown in Fig. 3. At the station 1 the flow was northerly

with an onshore component. A weak southerly flow was also encountered at the station 2 with an offshore component at 25 and 30 m sandwiched between the onshore flows at the surface and bottom layers.

### Residual currents

The residual currents at these two stations differ very much in spite of the geographical proximity between the two (Fig. 4). At the station 1, the flow was NE except close to the surface where it flowed onshore. Maximum speed of  $0.09 \text{ m sec}^{-1}$  was observed at mid-depth. The pattern at station 2 was entirely different. Here

it showed a clockwise twist from the surface to mid-depth and a reverse twist from mid depth to near bottom. Maximum speed of  $0.07 \text{ m sec}^{-1}$  was observed at 53 and 40 m depths and it was directed onshore.

An interesting feature observed was that the offshore component was totally absent at the station 1. It was again nearly absent at the station 2 (Fig. 4).

#### Temperature and salinity

Temperature and salinity variations were not very large. At the station 1, a depth-wise decrease in temperature was observed. Maximum ( $26.0^\circ\text{C}$ ) was at the surface, while the minimum ( $25.2^\circ\text{C}$ ) was near the bottom. Surface layers showed a diurnal variation in temperature, the maximum temperature was observed during the early hours of the afternoon. Salinity varied between  $34.8\text{‰}$  and  $35.1\text{‰}$ .

At the station 2, the water column was found to be isothermal from surface to bottom. Temperature at this station was about  $25^\circ\text{C}$  and salinity varied between  $34.8\text{‰}$  and  $35.1\text{‰}$ .

#### DISCUSSION

In spite of the winds, with their directions changing between NNE and NNW and the speed varying between  $2.5$  and  $10 \text{ m sec}^{-1}$ , the periodic turning of the currents to the north with the flood was observed at all the depths. This shows that the tide is the major current producing agent during this period. Almost similar conditions were reported in the month of March by NIO (Anonymous, 1976—Figs. 26 to 29).

To estimate the effect of winds on the residual currents, Ekman currents for finite depth were computed using the formulae given by Neumann and Pierson (1966), for the average wind speeds of  $7.5$  and  $6 \text{ m sec}^{-1}$  at stations 1 and 2 respectively and assuming steady northerly winds. The wind stress was calculated using the quadratic law preferred by Ekman and many other authors,  $\tau = 2.6 \times 10^{-3} \rho' W^2$  where  $\tau$  is the wind stress,  $\rho'$  is the density of the air and  $W$  is the wind speed.  $\mu$ , the coefficient of eddy viscosity, was calculated using the relationship established by Neumann between  $\mu$  and wind speed for fully developed seas.  $\mu$ , calculated using the above relationship agreed fairly well with the estimates by Thorade, Schmidt etc. (Neumann and Pierson, 1966).

The computations showed that at station 1, the speeds decrease from  $0.17$  to  $0.02 \text{ m sec}^{-1}$  and the directions change from  $209^\circ$  to  $227^\circ \text{ T}$  (True north) from surface to bottom. At the station 2, the changes in the speed and direction are from  $0.14$  to  $0.003 \text{ m sec}^{-1}$  and from  $226$  to  $285^\circ \text{ T}$  respectively. The residual currents obtained during our observations (Fig. 4) are in considerable variance with the computed speeds and directions of Ekman drift. Maximum currents were observed below the surface layers. At the station 1, the direction was about  $35^\circ \text{ T}$  and while at station 2, it swung between  $30^\circ$  and  $225^\circ \text{ T}$  indicating that the wind is not a major current inducing force during the period of observation and its effect was either negligible or was masked by the other constituents of currents.

The wind speeds used in our computations were considerably higher than

## *Currents off Bombay*

those indicated in various atlases for the month of February for this region: about  $2.5 \text{ m sec}^{-1}$  (Anonymous, 1952) and about 2 and  $3 \text{ m sec}^{-1}$  for 1963 and '64 respectively (Anonymous, 1972). However, their directions agree with ours. Hence it is possible that our results are over-estimates, implying that wind normally may not be the major current producing agent during this month.

Flood was northerly with an onshore component, while the ebb was southerly with an offshore component. This agrees with the West Coast of India Pilot (Anonymous, 1961) which states that flood is northerly from Konkan coast to Gulf of Cambay. Tidal currents at the station 2, farther from the coast, were faster. The higher tidal range during the observations at this station might have contributed to this feature. However, the computation of tidal currents for the standing waves, off the east coast of India, has shown maximum currents on the outer shelf (La Fond and La Fond, 1968). According to Sverdrup, Johnson and Flemming (1942), similar conditions hold good not only for the standing waves but also, in general, for such conditions when there is an onshore transport during some part of the tide and an offshore transport during some other part. This is true of Bombay and since the shelf is wide here, the maximum current is expected towards the outer shelf. The higher velocities found at the further station may, therefore, be viewed under this guideline.

A reduction in the current speed was observed at both the stations near the bottom due to the bottom friction. At the station 1, the flood was generally faster while the ebb was stronger at the station

2. The tidal currents showed a counter-clockwise rotation at the station 1, while at the station 2, it was generally oscillatory. At these stations, the offshore component was nearly absent. Strong northerly net flow was present at the station 1 while at the station 2, generally a weak southerly flow was observed. Residual currents were nearly unidirectional with depth at the station 1 while it was distributed within a wide range of angles at the station 2.

The results of these studies reveal interesting but paradoxical features. At the station 1, while there is a strong northerly net flow, at the station 2, weak southerly flow also prevailed at 15 to 40 m depths (Figs. 3 and 4). Although the data collected are somewhat inadequate to give definite reasons for these features, the following possibilities are suggested.

Eddies are established as a permanent feature of the ocean current systems. Such eddies are reported mainly from areas away from the tidal influence. However, studies in the estuaries and tidal inlets have shown the presence of eddies which are produced by the shear against the boundaries and which derive energy from tidal currents. Eddies with opposing currents were reported by Lævastu, Avery and Cox (1964) in coastal water off Hawaii islands. These were mainly caused by the presence of islands and irregular bottom contours. Since such features are not present off Bombay, one may be tempted to attribute the opposing net flows observed off Bombay to the presence of eddies in the basic flow during the transition period. Detailed studies are needed to establish the presence of any such eddies and to assess their time and space scales.

As stated earlier, February is a month of transition from counter clockwise to clockwise general circulation in the Arabian Sea. Our observations suggested that the seasonal northerly flow was probably still prevailing near the shore (station 1), while a weak southerly flow was also present farther away from shore (station 2). Such opposing flows are possible if reversals do not occur simultaneously across the shelf and in stead, shift gradually shoreward.

It is rather difficult at this stage to arrive at a definite inference with the available data. However, this raises oceanographic curiosities about this com-

plex system which responds differentially to the two monsoons. Observations over a longer period, with the moored current meters, are necessary in the shelf region to come to a definite conclusion.

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