

Coastal circulation off Ratnagiri, west coast of India during monsoon seasons: a numerical model study

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Received 31 January 2013; revised 20 February 2013

Present study is the coastal circulation modelling off Ratnagiri under the influence of winds and tides. A two-dimensional hydrodynamic model MIKE 21HD has been used to simulate tides and currents, and model results are in a good agreement with the measurements. In July, representing the southwest monsoon, wind is relatively strong, onshore current component is more pronounced; but, tidal variations are masked to a great extent by the wind driven circulation. Relatively stronger winds of the order of 8 m/s, persisted for a longer period, and that contributed to the southward flowing coastal current which is more consistent in its direction and magnitude. Meridional current has a prominent southward direction with a maximum alongshore speed of ~0.41 m/s. Zonal current is too weak to have a considerable impact on the circulation pattern. Prominent circulation is southward, irrespective of the seasons.

[**Keywords:** Tides, Winds, Coastal circulation, Monsoons, Arabian Sea]

Introduction

Coastal currents are affected by wind-driven (Ekman), tidal, surface wave and geostrophic flows. As the distance from the coast increases, the currents are influenced by large scale near surface flow in the open sea. The contribution from the above depends on the geographic location, continental slope and the coastal orientation. Circulation patterns along the west coast of India are studied mostly through analyzing the physical and chemical properties of seawater^{1,2,3,4}. Various researchers^{5,6,7,8,9,10,11,12,13,14} studied the coastal currents off west coast of India in detail, directly from the current measurements. Numerical studies carried out for this region emphasised the importance of local and remote forcing for the circulation in the Arabian Sea^{15,16,17,18,19,20,21}. A detailed examination of the mechanisms forcing the seasonally reversing, trans-basin monsoon currents in the open ocean is presented by²². It was found by¹² that off Goa during March-April, the West

India Coastal Current (WICC) was driven by local winds only at periods less than ~10 days, with remote forcing contributing at longer periods.

Spatial and temporal changes in surface topography in coastal region is a response to the balance of Pressure Gradient Forces (PGF) with combined effects of irregular bathymetry (e.g. sandbars, channels), varying bed resistance (dependent on depth, grain size and bed-forms), wave effects (run-up and set-up) and freshwater discharge²³. Winds along the WCI possess a well defined annual cycle. Even in the absence of horizontal advection of fluxes across the boundaries of the ocean, coastal currents forced by winds cause changes in the local mass field by forcing coastal upwelling or downwelling, thereby influencing the static level³. Tides along the WCI are mixed with the semi-diurnal constituents M2 and S2 and diurnal constituents K1 and O1, among which M2 is the most significant component.

The present study aims at modelling the flow patterns prevailed off Ratnagiri, west coast of India during the southwest and northeast monsoons of 2008. Measurements available for the above seasons have been used for the validation of model results. Based on the modelling results, circulation pattern off Ratnagiri is discussed.

Materials and Methods

Study Area

In the coastal belt of Ratnagiri, tropical humid climate prevails throughout the year. Ratnagiri is surrounded by Sahyadri hills in the east and the Arabian Sea in the west. Area of study extends from 16°23'N, 72°00'E to 17°35'N, 73°30'E (Fig.1). Study area is hilly; shoreline is highly irregular; coastal

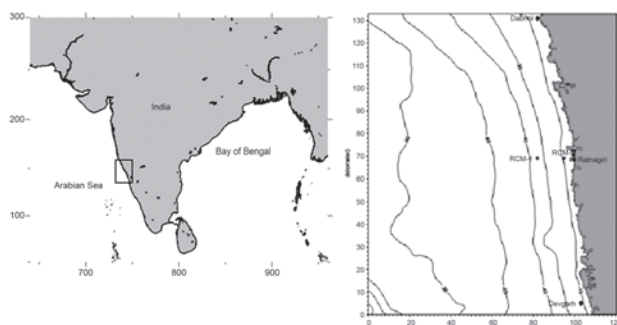


Fig.1. Model domains showing (a) Indian Ocean and (b) Major locations of the study area

region comprises of promontories and cliffs at several locations. River runoff is maximum during SW monsoon and minimum in other seasons.

Width of the continental shelf on the WCI varies considerably from south to north. The continental shelf of the study region is relatively wide²⁴. Shelf break on this coast is approximately along the 200 m depth contour and the shelf region is more than 100 km wide and less than 200 m deep. Circulation is expected to be dominated by shallow water processes, the components of which are tides, local winds, and possibly runoff from adjoining rivers and large-scale wind-driven circulation. Northward seasonal coastal current along the WCI during the NE monsoon is

known to have its core located on the shelf break²⁵. It should be exerting at least some influence on the circulation on the shelf. The 200 m isobath runs almost parallel to the coastline which indicates that the depth contours are aligned more or less parallel to the coastline in most of the region. On moving offshore from the 200 m isobath, the depth varies rapidly from 200 m to 1000 m.

Model used

A two-dimensional hydrodynamic model MIKE21-HD, which is an advanced numerical modelling for hydrodynamics, waves, sediment transport and ecological modelling²⁶ was used. This model has been extensively used in the simulation of hydrodynamics, water quality, wave dynamics and all related processes in coastal areas²⁷. The model was used for studying the tide driven currents and residual eddies in the Gulf of Kachchh²⁸. MIKE21 was also applied as a basic tool for the estimation of DO-BOD (Dissolved Oxygen - Biochemical Oxygen Demand) off Kochi, WCI²⁹. The model has been used by³⁰ for studying oil spill movement off Goa. The thermohaline structure of Gulf of Kachchh was studied by³¹ using MIKE21 HD. Using MIKE21,³² studied the abundance of fish larvae that accumulated in the northern Gulf of Kachchh (GoK), WCI. This model was used to estimate residence time of pollutants in the GoK³³. The barnacle larval dispersion along the west coast of India was studied by³⁴ setting up the numerical simulations using MIKE 21 particle analysis module. Model can incorporate flooding and drying conditions of exposed areas such as shoals, mud flat, sand bars, etc., and thus the areas that are prone to continuous flooding and drying can be treated more realistically.

Simulation of tides and currents has been carried out by solving the following 2D shallow water equations of mass and momentum²⁶. To solve 2D shallow water equations using finite difference numerical methods, structured numerical grids were used to define the bathymetry of the study area. Grid spacing of 500m in both x and y directions was selected such that the perturbations along the boundary could be diminished and the relevant

features for our study could be resolved. The bathymetry file was created by digitising the depth values obtained from the NHO (Naval Hydrographic Office, India) charts. The model domain is bounded by the latitudes $16^{\circ}23'N$ to $17^{\circ}45'N$ and longitudes $72^{\circ}23'E$ to $73^{\circ}30'E$, with 244×266 grid points (Fig. 1). Eastern boundary of the domain is a closed boundary, marked by land areas along the coastline, where the depth value is zero. The western boundary is taken along $72^{\circ}23'E$, where the depth values were high, with maximum depth = 230 m in the south western part of the boundary, at a distance of ~ 120 km offshore. Alignment of bathymetry in the domain follows the alignment of coastline (NW-SE direction). There are three open boundaries: west, north and south. Through these boundaries, the exchange of fluxes and momentum occurs. The model domain was selected in such a way that the region of interest and the measurement locations for calibration and validation were away from the boundaries.

Tidal levels with appropriate phase lag and no cross flow conditions were used at the boundaries to simulate prevailing flow. Surface elevations were generated at the boundaries (northern boundary, Dabhol: $17^{\circ}35'N$, $73^{\circ}11'E$); southern boundary, Devgarh: $16^{\circ}23'N$, $73^{\circ}23'E$) using Admiralty method of prediction of tides²⁶ with six major tidal constituents M2, S2, K1, O1, F4 and F6. The tide elevations at these stations were linearly interpolated to obtain the water level boundary conditions along the north and south open boundaries, and these were used for forcing the HD model. The tidal height at the western boundary is interpolated between the values of north and south water levels whereas the eastern boundary is closed. Model runs were carried out using the following calibration coefficients: wind friction factor = 0.0026, Manning's number = $38 \text{ m}^{13} \text{ s}^{-1}$ and horizontal eddy viscosity = $0.5 \text{ m}^2 \text{ s}^{-1}$.

The recorded data of wind speed and direction of Autonomous Weather Station (AWS) at Ratnagiri were available for every ten minutes to validate the blended wind data - derived from a space and time blend of QSCAT-KU2000 scatterometer observations and NCEP analyses. Blended data provides low

frequency (6 hourly), high resolution ($0.25^{\circ} \times 0.25^{\circ}$) winds. Inter-comparison of the blended wind time series at three locations in the domain showed very negligible variability in speed and direction. Therefore, the blended wind at Ratnagiri was kept as uniform over the whole domain. The blended wind rose diagram for the period 23 January to 23 February 2008 (Fig. 2 a & b) shows that the prominent wind direction was south. But, since the wind was weak during this season, it could not produce significant effect on the flow pattern. northwesterly component was strong during this period. Because of the

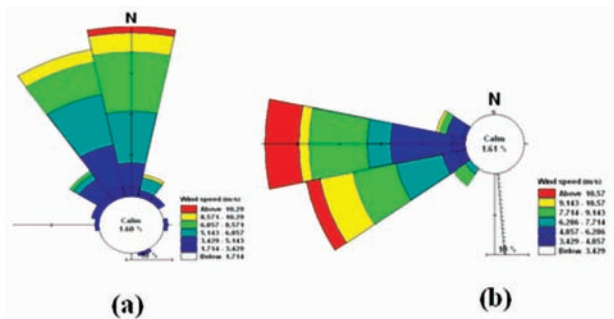


Fig. 2. (a) Wind-rose diagram (January-February, 2008) during NE monsoon, (b) Wind-rose diagram (June-September, 2008) during SW monsoon

geographic location of the study area, W and SW winds have greater influence on coastal dynamics. Wind friction coefficient for strong and moderate wind is usually 0.0026, whereas, we have used the value of 0.0013 as winds were weak²⁶.

Results and Discussion

The MIKE 21 HD model was setup to study the hydrodynamics along the west coast of India during the northeast monsoon. Sea levels due to tides were given as the boundary input for the model domain on the west, south and north open boundaries. Eddy viscosity was specified as per the Smagorinsky constant and bed resistance by dimensionless Manning number using a variable resistance file with high resistance along the boundaries. HD model gives water levels and density fluxes, from which the current magnitude and direction have been extracted. Model was run for one month to include both spring and neap tides. Hydrodynamic simulations for NE

monsoon, after calibration and validation, showed very good match between the measured and modelled water levels and currents. Hence, the same set-up was used to run the model for the month of July 2008 (SW monsoon) by changing only the winds and water levels.

Water levels obtained from the model were compared with predicted water levels (Fig. 3), and the match is very good, indicating that the model is well calibrated. Current meter data at the depth of 35.6 m off Ratnagiri region was used for validating

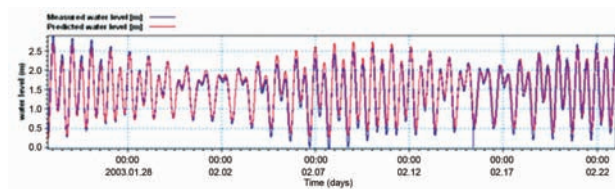


Fig 3. Comparison between measured and simulated water levels off Ratnagiri

the simulated currents during the study period. Comparison yields reasonably good match between the measured and simulated currents. Fig. 4 (a & b) shows the modelled versus measured velocity components (u,v) of currents. The discrepancies may be due to point measurement, which is not true representative of depth-averaged conditions simulated by the model. Also, in general currents are less than

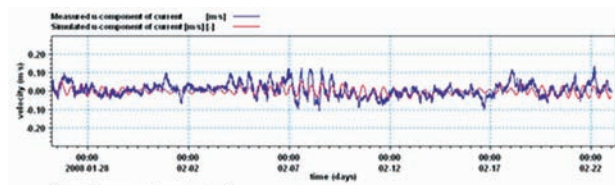


Fig. 4a. Comparison between measured and simulated u-component of currents off Ratnagiri

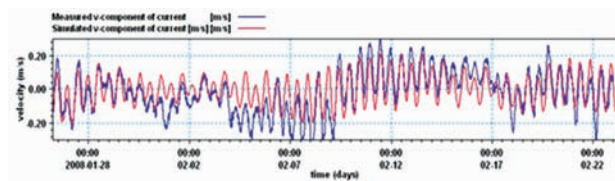


Fig. 4b. Comparison between measured and simulated v-component of currents off Ratnagiri

0.1 m/s in the case of u component (zonal current) and less than 0.25 m/s in the case of v component (meridional current).

Water level

Simulated surface elevations have been recorded for every one hour. The simulated water levels for the NE and SW monsoon months off Ratnagiri show that the surface elevation is primarily contributed by tides. Common pattern observed in both the seasons is that peak currents are associated with high water levels. But, we find that there is no considerable change in water level variations, when the model was run with winds. During January-February, the maximum water level is found to be nearly 2.5 m with an average spring tidal range of 1.9 m and neap tidal range of 1.2 m (Fig. 5a). Maximum tidal range along the Ratnagiri coast during NE monsoon is ~2.3 m, and during SW monsoon ~2.6 m (Fig. 6a).

Currents

Tidal currents are significant in this region. In both the seasons, the current speed during ebb tide is

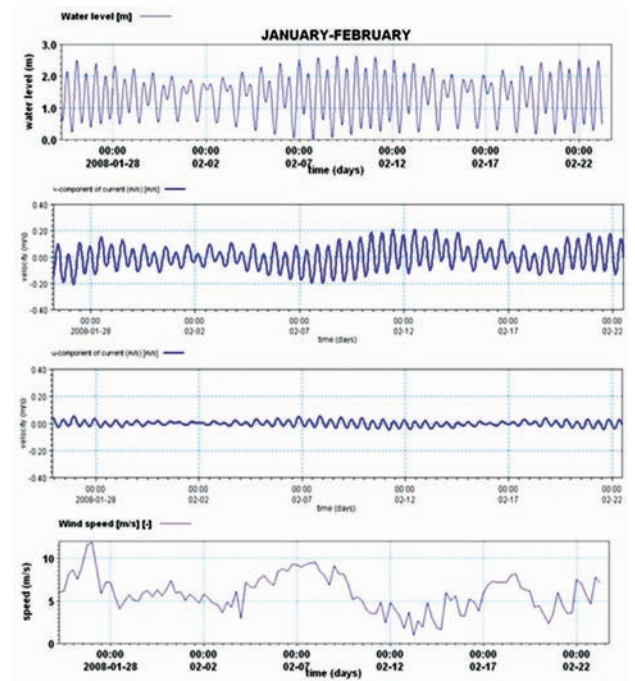


Fig.5. Time series plot for (a) surface elevation (b) v-component of current (c) u-component of current and (d) wind used during NE monsoon period (Jan-Feb 2008).

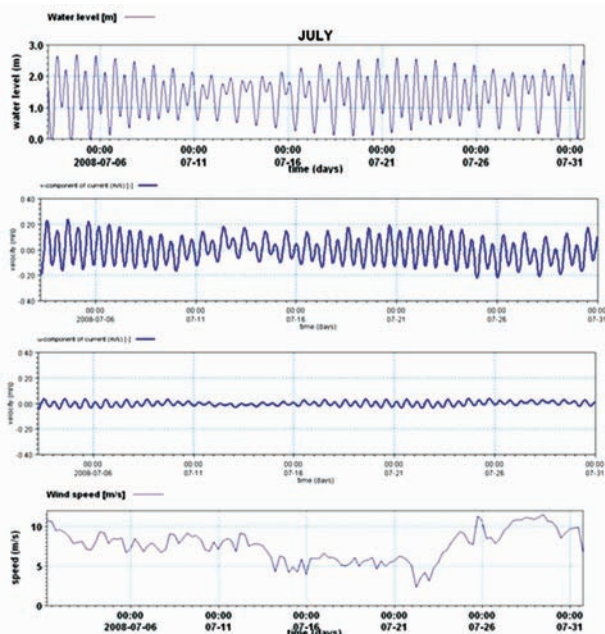


Fig.6. Time series plot for (a) surface elevation (b) v-component of current (c) u-component of current and (d) wind used during SW monsoon period (July 2008)

stronger than the flood tide since the wind driven currents are also in the same direction. During ebb tide, the predominant flow is towards south and during flood, the flow is towards north (Fig. 7). Tidal currents oscillate mainly in the alongshore direction with little net cross-shore current. The onshore and offshore currents (u-component) were weaker, compared to the alongshore currents (v-component), irrespective of the season. There is no contribution by the fresh water discharges during NE monsoon period, but we can expect some contribution during SW monsoon period, though very minimal. Magnitude of southward flow is higher than that the northward flow. The net alongshore current is found to be southward both during July and January-February. The current meter data as well as the simulation results show that the alongshore component of velocity goes on decreasing towards the coast. This may be due to increase in bed friction. At times, the u-component of simulated current shows some variation with the measured current, which is due to very weak currents, of the order of 0.05-0.10 m/s (Fig. 4a). In January, the prevailing wind is southwards. Interesting feature is that the principal alongshore current during NE

months varies in direction, that is, alongshore component is northwards when the wind speed is very less; at that time, it is the flood that drives the water northwards overwhelming the opposing forces like wind (Fig. 5).

Fig. 7 (a & b) shows the flow direction off Ratnagiri during January-February 2008. maximum current speed during this period is around 0.38 m/s with southeast direction. This is in agreement with the results of modeling by¹³ that the coastal current

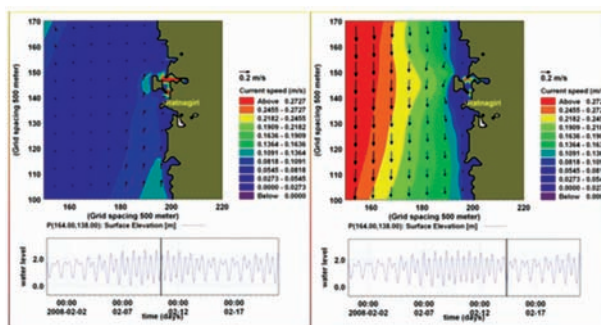


Fig. 7. Flow pattern during (a) flood tide and (b) ebb tide (Jan-Feb 2008)

influences the tidally driven flow, though marginally. Simulated currents show that the currents are having distinct variability corresponding to the tide. It may be noted that in the poleward flow, density driven flow is the existent force that drives the surface water northwards. However, in the present study, even without including the density effects, the simulated current matches well with the measurements obtained from RCM deployed at 35.6 m (~ 5 km seawards from the coast). This shows that the density driven current vanishes in the nearshore region.

In July (representing SW monsoon), wind speed is relatively higher, and onshore component is more noticeable. Fig. 8 (a & b) shows the flow direction off Ratnagiri during July 2008. During the SW monsoon, tide variations at Ratnagiri were masked to a great extent by the winds. The northward flow during flood is not noticeable. Relatively stronger winds of the order of 8 m/s, persisted for a longer period, and that contributed to the southward flowing alongshore current which is more consistent in its

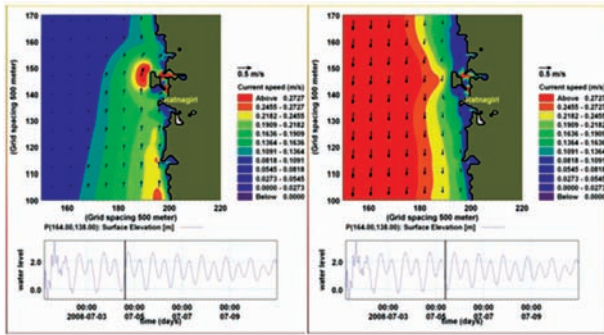


Fig. 8. Flow pattern during (a) flood tide and (b) ebb tide (July 2008)

direction and magnitude. The v-velocity component has a prominent southward direction with a maximum alongshore speed of ~ 0.41 m/s. In general, the flow indicates that the maximum current speed is observed during ebb than during the flood tide.

Coastal circulation

The circulation along the WCI is dominated by the WICC during both the monsoon seasons. The WICC moves against weak alongshore wind component during the NE monsoon. Since our study region belongs to coastal ocean, the density driven currents have the least significance. Main driving forces that frame out the flow here is the winds and tidal currents. Model results are in good agreement with the measured data, indicating that the flow is purely the effect of wind and tide induced forces. prominent circulation is southward, irrespective of the seasons. But, the intensity of flow is relatively strong during the SW monsoon period. The u-component of current is too feeble to have a considerable impact on the circulation pattern. Flow pattern also shows that apart from wind and tide, the bathymetry also plays a crucial role in driving the water as bathymetry shows an upward slope to the north. The WICC is having a poleward component during the NE monsoon which is contributed mainly by the equatorially trapped Rossby and Kelvin waves as well as coastally trapped Kelvin waves^{35, 36}. But, the poleward flowing WICC becomes weaker with the increase in latitude³⁷. This might also favour the southward flow during NE monsoon as evident by the measured currents.

Conclusions

Results obtained from the hydrodynamic model are validated with the measured currents, and the match is reasonably good. Hence, the model can be further used for the simulation of hydrodynamics of other months also. Study suggests that in the regions very close to coast, the density driven currents have negligible impact, whereas, it is the combined effect of tidal oscillation and wind forcing frame out the coastal circulation. Strong flow during the SW as well as NE monsoons is an implication of how the wind pattern alters the speed and direction of currents. limitation of modelling is the lack of sufficient boundary data. Model has provided a general understanding of the surface flows off Ratnagiri region. The inclusion of river runoff and wave-induced currents may reproduce better flow pattern. The effect of salinity is of vital importance when the stratified ocean water close to the well-mixed coastal waters is considered.

Acknowledgements

Authors thank Dr. S. W. A. Naqvi, Director, National Institute of Oceanography (NIO), Goa for his interest in this study. The NIO contribution number is 5424.

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