COHERENS: a hydrodynamic model validated for the west coast of India

Betty John[1], P. P. Saheed[1], Carlos Franca[2], P. Vethamony[1,]* and Edmo J. D. Campos[2]

[1]CSIR-National Institute of Oceanography, Goa 403 004, India
[2]Instituto Oceanografico -Universidade de Sao Paulo, Praca do Oceanografico, Sao Paulo-SP, Brazil

COHERENS (COupled Hydrodynamical and Ecological model for REgioNal and Shelf seas), a 3D hydrodynamic multi-purpose model, has been implemented for the coastal and shelf seas of eastern Arabian Sea to study the flow characteristics. The model has been tested and verified with one month measurements of surface and bottom currents collected off Mangalore, Ratnagiri, Mumbai and Dwarka on the west coast of India (WCI). After calibration, the model was allowed to perform under tide and wind forcings. The flow characteristics at these select locations have been well reproduced by the model. A shift in current direction from south to southeast has been observed at several occasions, and this could be attributed to shamal events. The low amplitudes of the residual currents in the measurements off Mumbai and Dwarka suggest that the influence of the West India Coastal Current is weak or negligible in the northern part of the WCI and the currents are mainly tide-dominant. Certain discrepancies are noticed especially in the southern domain, off Mangalore, where the shallow water dynamics is not only driven by the local wind forcing and tides, but also by the remotely driven currents. In order to get a comprehensive picture of the prevailing dynamics, the model domain has to be extended to the entire Indian Ocean.

Keywords: Coastal and shelf seas, hydrodynamics, numerical modelling, residual current.

OCEAN numerical models have become quite realistic as a result of improved methods, faster computing facilities and availability of global datasets. Models now treat global domain to basinscale to coastal regimes. The economic importance of the coastal zone has led to the development of many different numerical shelf models for describing tides and coastal currents. Over the past few years, several numerical models have been attempted worldwide for oceanic studies. Progress in understanding the fundamental processes of coastal circulation has been limited by the meagre *in situ* observations. Meanwhile, ocean circulation models make it possible to use the simulations to fill up the gap of observations and explore various physical processes[1–4].

In the present study, we show the capability of the COHERENS (COupled Hydrodynamical and Ecological model for REgioNal and Shelf seas) model in representing the real hydrodynamic conditions along the west coast of India (WCI). Though several models are available to study the circulation pattern, the COHERENS model has not been used earlier to study the circulation in this region. It is a freely available model which can be further used for combined studies such as biogeochemical, contaminant and sediment transport in the region of interest by coupling with its sub-modules[5,6]. This model has been successfully implemented for the North Sea and Bohai Sea[7–9]. COHERENS has been coupled with other models as well to study biogeochemical features, sediment transport and wave motions[10–12]. For the present study, we have selected four locations along the WCI according to the availability of observed data. Since we do not have the simulated results of temperature and salinity of the study region, we used the available surface and bottom current data of the study locations.

Understanding the coastal ocean circulation is societally relevant since the coastal area is considered as one of the major population centres in the world. The coastal zones in India need more attention because of their high productive ecosystems, population concentration, exploitation of natural resources, etc. The WCI forms the eastern boundary of the Arabian Sea basin. Various studies have been carried out on the coastal currents and flow patterns along the WCI using both *in situ* measurements and model results[13–18]. Hydrodynamic modelling is a pre-requisite to the ecological studies as it influences the biological and chemical processes in the region[19].

The main objective of the study is to examine the capability of the COHERENS model in representing the hydrodynamic conditions prevailing in the shelf seas along the WCI and to discuss the circulation pattern of selected locations along the WCI using the model results. Since the chemical, biological and morphological processes are linked to the hydrodynamic circulation patterns, the 3D hydrodynamic model results in the regions will provide evidences to predict scenarios in the coastal waters like

*For correspondence. (e-mail: mony@nio.org)

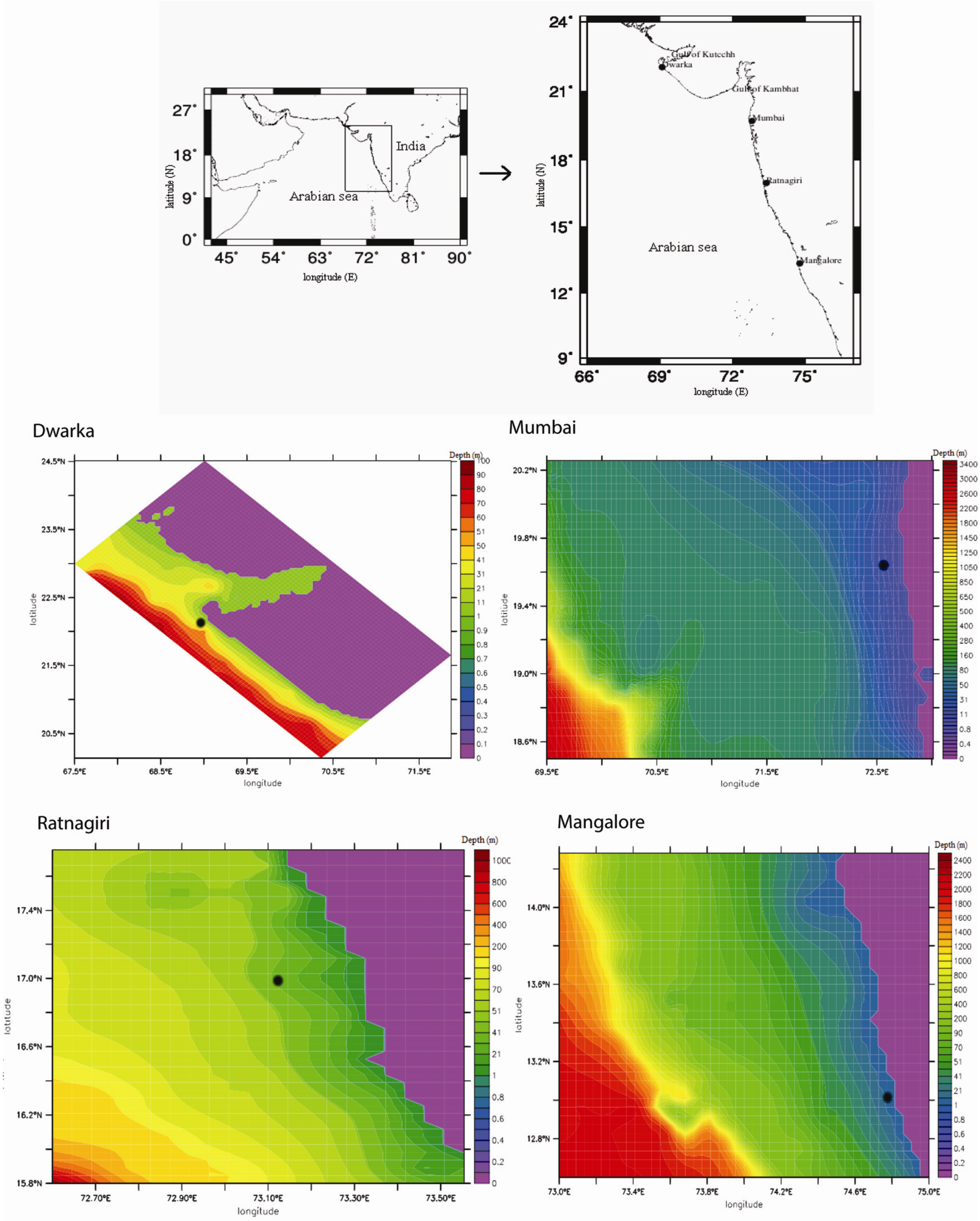

Figure 1. Model domain and bathymetry of the local domains. RCM locations Dwarka, Satpati (Mumbai), Ratnagiri and Suratkal (Mangalore) are marked.

oil spills, transport and fate of constituents in water such as sewage discharges, fish larvae and sediments.

Study area and data used

The study area lies in the WCI approximately between 12.0° and 23.0°N lat. Four locations were selected for this study according to the availability of observed data which were used for validation and comparison of the model results. The shelf seas off Mangalore, Ratnagiri, Mumbai and Dwarka (Figure 1) were considered in this study as measurements are available and these regions represent the southwest (Mangalore), northwest (Dwarka) and central west coasts of India (Ratnagiri and Mumbai). WCI is a dynamically vibrant coastal belt with anthropogenic influences from recreational, industrial and commercial activities. Beach tourism, industries, shipping, fishing activities, etc. take place in this region. A good understanding of the hydrodynamics helps us to study activities/environmental issues like oil-spill mitigation, effluent discharge, etc.

The western continental shelf of India widens from south to north and hence the tidal range increases towards north. The continental shelf off Mangalore extends up to 75 km from the coast[20], and widens off Ratnagiri which is more than 100 km from the coast, whereas off Mumbai it extends up to 250 km (ref. 21). Further north of Mumbai, the continental shelf width becomes narrow. In all the selected locations the winds are mainly westerly or south westerly and the wind speed is strong during the SW monsoon period. The WCI is exposed to seasonally reversing monsoon winds, which have an important bearing on the hydrography of the coastal waters. Since the seasonal variations in temperature are small in the tropics, the change in temperature plays a negligible role in forcing seasonal changes along the west coast[22]. However, during the southwest monsoon, variations in the temperature are important in the northern Arabian Sea, where cooling by the cold winds blowing from the northeast in winter forces a drop in temperature in the upper ocean[23,24]. The depth contours up to some extent are almost parallel to the coastlines in all locations. The currents are dominated by tides, which are mixed with semi-diurnal constituents M2 and S2 and diurnal constituents K1 and O1 (ref. 25). During the seasons, the current direction fluctuates between northwest and southeast directions. The along shore (AS) component of the currents in the north Indian Ocean (NIO) is much stronger than the cross shore (CS) component of the currents, which is due to the influence of wind-driven southwest (SW) and northeast (NE) monsoonal circulation. The AS components (north–south) in these regions are influenced by tides, whereas the CS components (east–west), by winds. The coastal flow can be considered as the tidal currents flowing parallel to the coast with some onshore drift under the influence of the existing wind pattern[26].

Surface and bottom currents were measured at different locations along the WCI using Recording Current Meters (RCM-9-LW; Aanderaa Data Instruments, Norway). The instruments were deployed at four locations: off Suratkal (Mangalore), Satpati (Mumbai), Ratnagiri and Dwarka, among which bottom measurements were available at Satpati and Dwarka only (Figure 1). The RCM-9-LW has an accuracy of ± 0.15 cm/s for current speed and ± 7.5° for current direction and a depth range 0–300 m. The measurement locations and durations are listed in Table 1. The measurement period off Mumbai includes the passage of the cyclone Phyan (during November 2009), which moved through the eastern Arabian Sea and made a strong impact on the circulation along the WCI[27]. The tide gauge measurements were conducted off Mumbai along with the current meter observations. The meteorological forcing data have been provided at six hourly intervals from the NCEP/NCAR (National Centre for Environmental Prediction) reanalysis data set[28].

Table 1. Details of measurements

Location	Latitude/ longitude	Depth (m)	Data duration
Dwarka	22°04.634′N 69°05.252′E	15	December 2007–January 2008
Mumbai	19°43.973′N 72°36.978′E	16	October–November 2009
Ratnagiri	17°00′N 73°7.2′E	35	January–February 2008
Mangalore	12°71.466′N 74°59.033′E	7	April 2007

Description of the COHERENS model

Luyten *et al.*[7,8] developed COHERENS, the three-dimensional hydrodynamic model for shelf seas, which resolves mesoscale to seasonal scale processes. It is a nonlinear baroclinic model which solves Navier–Stokes equation under the hydrostatic approximation in sigma coordinate system in vertical. The model solves numerically the momentum equation (employ the Boussinesq approximation), vertical hydrostatic equilibrium, continuity, temperature and salinity in spherical coordinates by coupling between the external barotropic mode and the internal baroclinic mode. The surface elevation and the depth-integrated current velocities are calculated using the barotropic mode, whereas the three-dimensional currents, temperature and salinity are determined using the baroclinic mode. The density is calculated using the equation of state, which is utilized for the calculation of buoyancy. Vertical eddy viscosity coefficients are calculated using turbulent closure methods. The vertical coordinates of the model solve the problems by considering the steep topography and strong stratification. The model programme contains many switches, which can be used to select the model grid, enable/disable different processes, set the forcing and boundary conditions and enable/disable different modules. The total variation diminishing (TVD) scheme is applied to the advection of momentum and scalars. Surface stress and heat flux are calculated as a function of wind and sea–air temperature difference using the bulk formulae of Kondo[29]. A quadratic friction law is applied at the seabed using a roughness length of 3.5 mm. The depth integrated current at open-sea boundaries is determined using the method of characteristics[30].

Model set-up

The major advantage of the sensitivity analysis of a model is its ability to evaluate the impact of the perturbation quantitatively[31]. In this study several sensitivity runs have been made analyse effects of different forcing conditions in each domain. Initially, we have run the model without wind forcing; the model was solely forced with tides in the open boundaries. The wind forcing and other meteorological parameters were then added to the model for executing the realistic conditions. Several numerical experiments were carried out, considering different bottom drag coefficients. Numerous grid sensitivity runs have been performed by changing the number of grids at the east–west open boundaries and the north–south open boundaries of the respective domains. For obtaining a clear simulation of bottom currents, the vertical layers were also changed accordingly. As we are not considering the baroclinic variations in the present study, different vertical mixing schemes were not experimented with.

The model equations were distinguished on an Arakawa C-grid[32]. All the governing equations were solved using mode-splitting technique, which increases the computational performance of the model[33]. A spherical coordinate system was applied to generate horizontal (X and Y) grids and a sigma-vertical coordinate system was applied to generate vertical (Z) grids in the model. The sigma coordinates vary between 0 at the bottom and 1 at the surface. A grid resolution of 5 km × 5 km was considered in the horizontal plane and 20 layers were considered in the vertical plane in each domain. The overall grid cells are 36,000 (45 × 40 × 20) off Mangalore, 19,800 (22 × 45 × 20) off Ratnagiri, 63,200 (79 × 40 × 20) off Mumbai and 84,600 (90 × 47 × 20) off Dwarka. The domain for Dwarka was rotated 45° in order to keep the western boundary parallel to the shelf and the remaining domains were kept unchanged as the shoreline is nearly parallel to the continental shelf. The extent of each domain is given in Table 2.

The model bathymetry has been generated by linearly interpolating the bathymetry data obtained from GEBCO (GEneral Bathymetric Chart of the Oceans; British Oceanographic Data Centre (BODC) 2003)[34] with a spatial resolution of 1′ × 1′. The north, south and west boundaries are open, while the east boundary is closed for all domains, except for Ratnagiri. The model was forced with predicted tidal elevations at the open boundaries. The prediction of tidal elevation at the boundaries was carried out using AG95 (Andersen–Grenoble, version 95 model), which utilizes the phase and amplitude of major tidal constituents[35,36]. The major physical parameters of the model are temperature, salinity and density, which should take the reference values considered as typical for the area of simulation. The reference values were used to initialize the temperature and salinity fields and to normalize the surface fluxes and the bottom stress by default. In the present study all domains have more or less the same values for these parameters; the values considered are 25°, 36 ppt and 1025 kg/m^3 for temperature, salinity and density respectively. Another important model parameter is the bottom drag coefficient (C^b_D), which is the function of roughness length that varies in each domain. The meteorological forcing data having a resolution of 2.5° × 2.5° were used to force the surface boundary of the model. The winds at 10 m height and sea-level atmospheric pressure were used. After the calibration phase the flow patterns and surface elevation of each domain were calculated under meteorological and tidal conditions. Simulations have been carried out for the months corresponding to the measurement periods for the purpose of model validation.

The model stability has been attained by keeping a minimum time-step interval which satisfies the CFL (Courant–Friedrich–Lewy) criterion as given below:

$$c\,\Delta t/\Delta x \leq 1, \qquad (1)$$

where Δt is the computational time-step, Δx the grid size, $c = \sqrt{gh}$ the wave celerity, g the acceleration due to gravity and h is the maximum depth in the domain. A time-step of 10s was considered for the simulations. The maximum depth in the four domains was 2100, 1050, 3000 and 92 m at Mangalore, Ratnagiri, Mumbai and Dwarka, respectively. The spin-up time for the barotropic simulation was one day (to reach the steady state).

The scatter plot (Figure 2) shows that the measured and simulated surface and bottom currents are well-correlated. The quality of the simulations has been tested by estimating the statistical parameters such as correlation coefficient, bias and rms-error (Table 3). The correlation coefficients between measured and simulated u and v

Table 2. Domain extension

Location	Longitude	Latitude
Dwarka	67.5–72.0°E	20.0–24.5°N
Mumbai	69.5–73°E	18.5–20.3°N
Ratnagiri	72.0–73.55°E	15.8–17.8°N
Mangalore	73.0–75.0°E	12.6–14.3°N

Table 3. Bias, RMS error and correlation coefficient of four locations

Location	Component	Bias (m/s)	RMS error (m/s)	Correlation coefficient
Dwarka – surface	u-velocity	0.020	0.070	0.64
	v-velocity	–0.001	0.089	0.66
Dwarka – bottom	u-velocity	0.01	0.046	0.77
	v-velocity	0.009	0.048	0.87
Mumbai – surface	u-velocity	0.009	0.083	0.52
	v-velocity	0.003	0.003	0.95
Mumbai – bottom	u-velocity	–0.010	0.057	0.69
	v-velocity	0.013	0.192	0.96
Ratnagiri	u-velocity	0.017	0.061	0.28
	v-velocity	0.033	0.101	0.70
Mangalore	u-velocity	–0.012	0.037	0.21
	v-velocity	–0.046	0.114	0.41

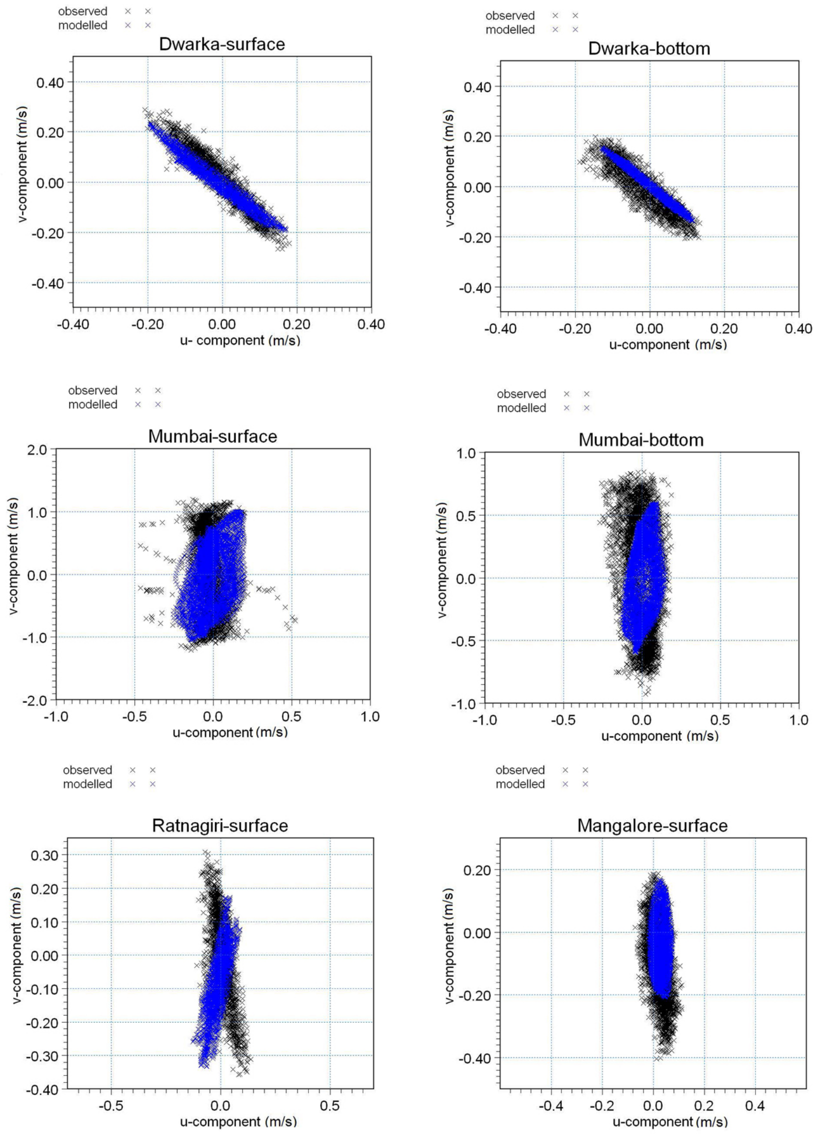

Figure 2. Scatter plots of surface and bottom currents.

components of surface currents off Dwarka, Mumbai, Ratnagiri and Mangalore are 0.64 and 0.66, 0.84 and 0.93, 0.28 and 0.70, and 0.21 and 0.41 respectively, and that of bottom currents off Dwarka and Mumbai are 0.77 and 0.87, and 0.91 and 0.97 respectively.

Results and discussion

The simulated AS and CS components of currents were compared with those of the measured currents at the surface and bottom (Figures 3–5). Table 4 shows the range of both measured and modelled values of the currents at all locations.

Off Dwarka

The mean AS current speed is stronger than that of the CS current as reported in the earlier studies along the WCI[13,37] except off Dwarka, where both the CS and AS components of currents vary between –0.2 and +0.2 m/s. The western continental shelf of India is narrow in the south and broadens northward up to the Gulf of Khambhat[21]. Further north it becomes narrower while approaching towards the Gulf of Kutchchh (GoK), where tide-induced currents are highly significant except during the SW monsoon, when the surface currents are driven by monsoon winds[38]. It is evident, while analysing the CS component of the measured currents off Dwarka, that there is a significant increase in magnitude (Figure 3). Almost the same amplitudes for both CS and AS currents in this region indicate the strong dominance of tide when comparing the other locations considered in the present study. Since Dwarka is situated close to the mouth of (GoK), the influence of tide in the coastal current will be more as there is an additional amplification of tidal constituents due to the funnel-shaped geometry of the Gulf[39].

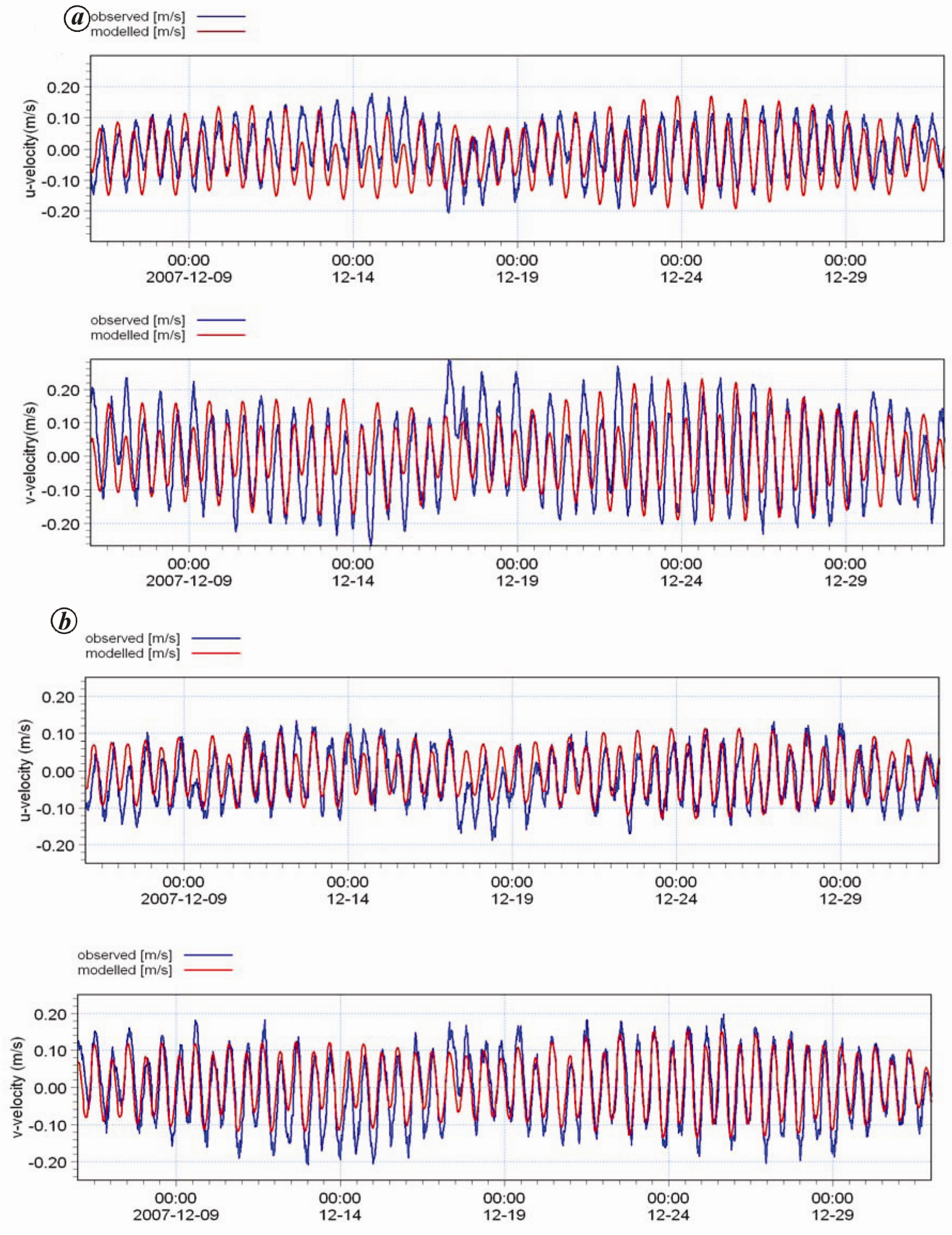

Figure 3. Comparison between measured and modelled (***a***) surface currents and (***b***) bottom currents off Dwarka.

This will enhance the CS and AS currents. Figure 6 shows the current pattern during the ebb and flood periods off Dwarka. The ebb currents which flow predominantly towards north are stronger than the southward-flowing flood currents. The coastal circulation off Dwarka, in the northeastern Arabian Sea, is dominated by tides with predominant north–south direction (Figure 7). The circulation off Dwarka, is also affected by large-scale horizontal advection from the GoK.

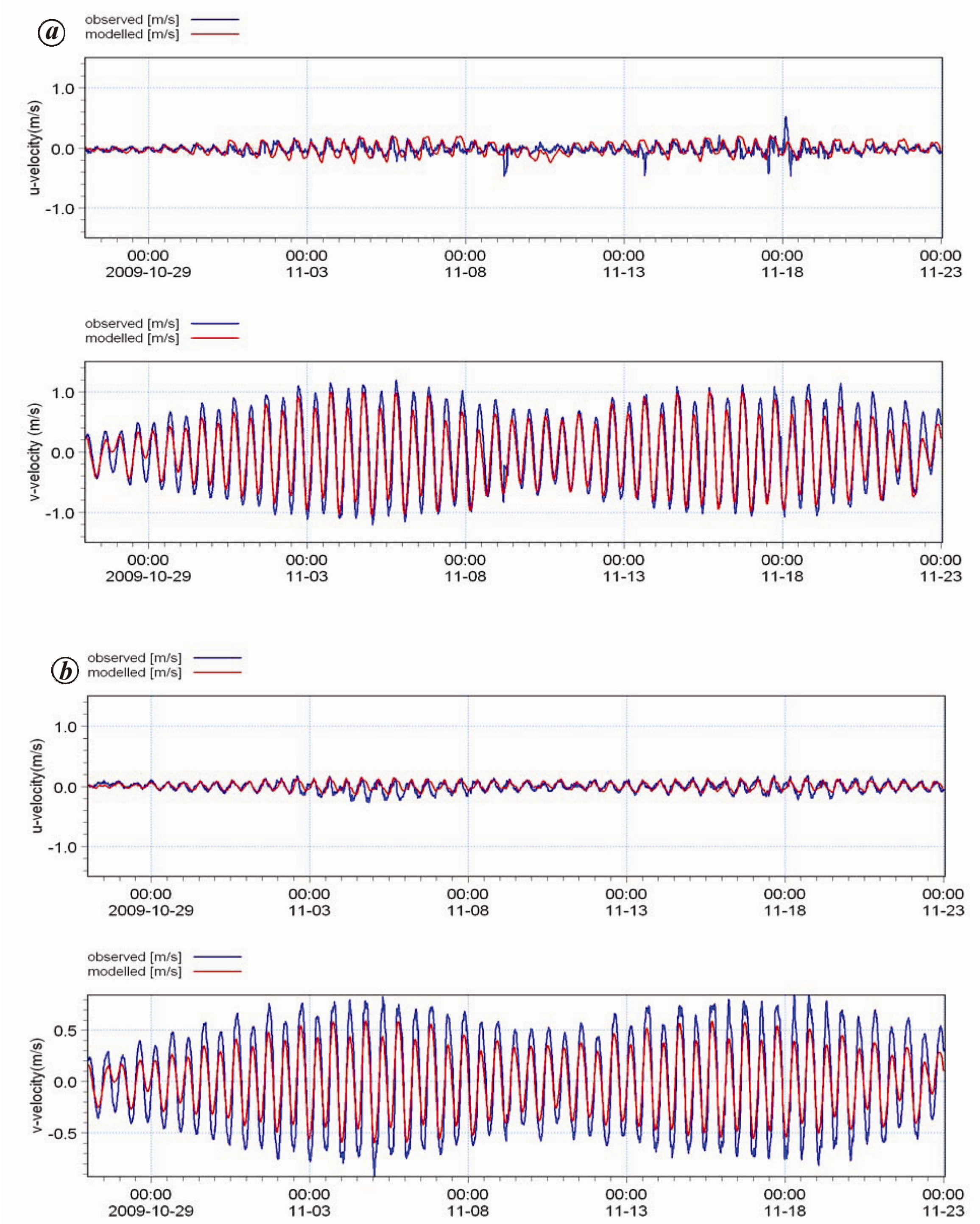

Figure 4. Comparison between measured and modelled (***a***) surface currents and (***b***) bottom currents off Mumbai.

Off Mumbai

The surface currents off Mumbai vary between –0.46 and 0.52 m/s for CS, and –1.2 and 1.19 m/s for AS components (Figure 4). The CS current component is less compared to the tide-induced AS current. Diurnal variation is observed in the measured residual currents even though the magnitudes are low compared to the tidal currents. The low amplitudes of the residual currents in the measurements suggest that the influence of West India Coastal Current (WICC) is weak or negligible in the northern part of the WCI. This indicates the influence of local land breeze and sea breeze on the circulation. The current flow is towards SW during the flood period and changes to NE

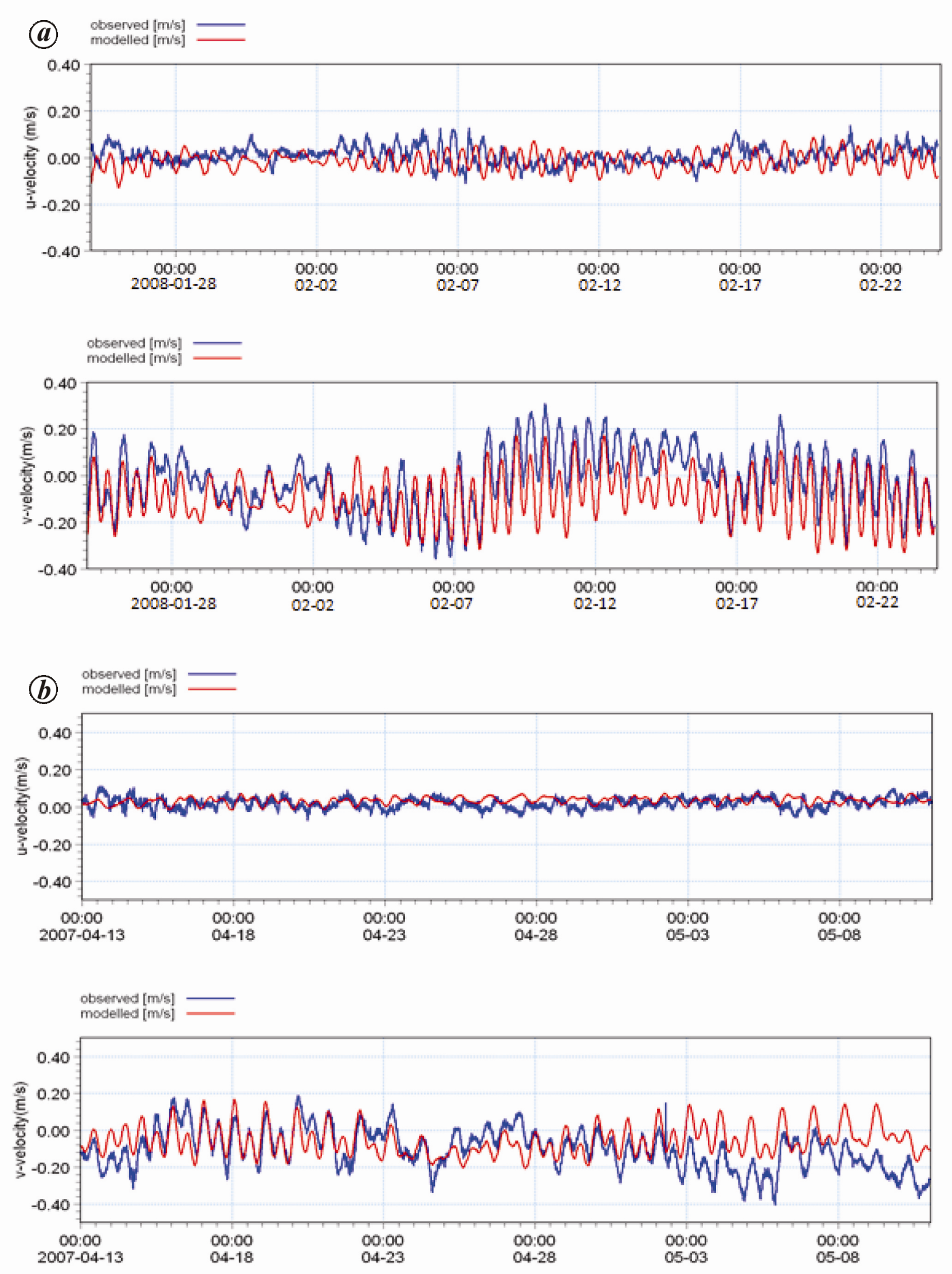

Figure 5. Comparison between measured and modelled surface currents off (***a***) Ratnagiri and (***b***) Mangalore.

during the ebb period (Figure 8). But the current direction changes to south and north near to the coast during the flood and ebb periods respectively. The strong southward-flowing flood current compared to the northerly ebb indicates the absence of northward-flowing density-driven currents in the measurement area. This is in agreement with the fact that the coastal currents in the region are dominated by tides compared to residuals like wind. The tides are mixed semi-diurnal type and so are the currents.

Off Ratnagiri

The tidal influence in the currents is relatively low in Ratnagiri compared to that of Mumbai, since the shelf

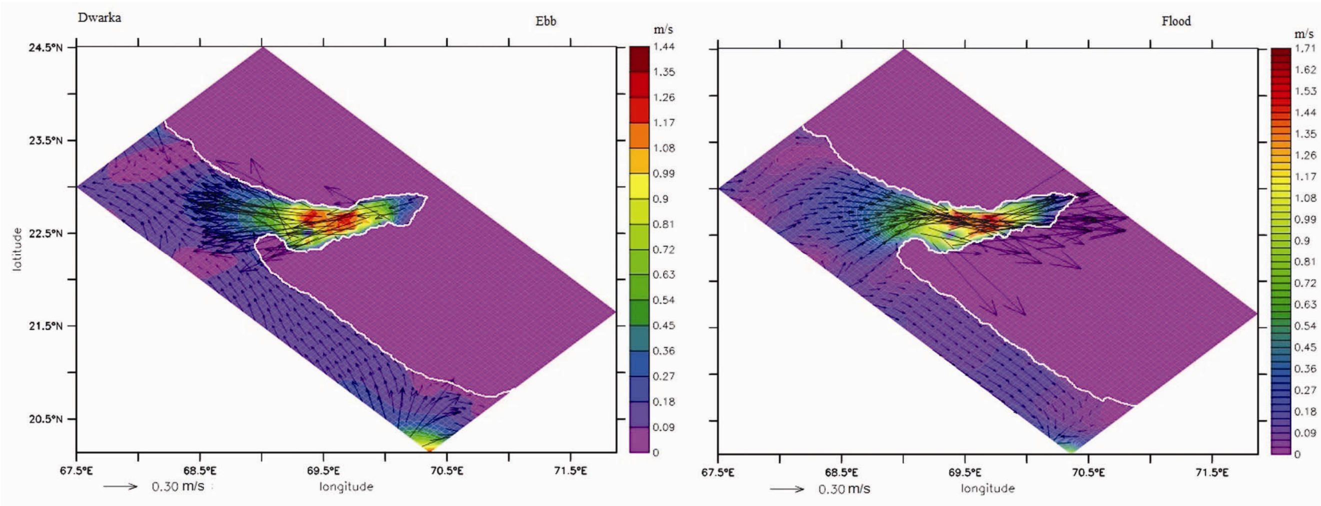

Figure 6. Simulated currents off Dwarka during ebb and flood periods.

Table 4. Range of measured and modelled values of currents at different locations

		Range (m/s)	
Location	Component	Measured	Modelled
Dwarka – surface	*u*-velocity	–0.207–0.178	–0.193–0.170
	v-velocity	–0.266–0.287	–0.193–0.230
Dwarka – bottom	*u*-velocity	–0.188–0.133	–0.128–0.114
	v-velocity	–0.208–0.198	–0.136–0.153
Mumbai – surface	*u*-velocity	–0.463–0.521	–0.256–0.201
	v-velocity	–1.206–1.195	–1.049–1.015
Mumbai – bottom	*u*-velocity	–0.270–0.187	–0.132–0.154
	v-velocity	–0.926–0.844	–0.595–0.593
Ratnagiri	*u*-velocity	–0.110–0.137	–0.127–0.086
	v-velocity	–0.357–0.308	–0.332–0.172
Mangalore	*u*-velocity	–0.071–0.111	–0.171–0.076
	v-velocity	–0.304–0.186	–0.208–0.167

width off Ratnagiri is narrow compared to that off Mumbai. The measured and modelled CS component of currents off Ratnagiri shows almost the same range of values, varying between –0.11 and 0.13 m/s (Figure 5 *a*). The CS component is weaker compared to the AS current component. The surface currents off Ratnagiri show a shift in current direction from south to southeast, which has been observed at several occasions. This could be attributed to shamal events which can be seen in the model results also. Earlier studies have investigated the effect of shamal events on the swells along the WCI[40]. The coastal currents have a principal southerly direction during the ebb tide as well as flood tide, though the magnitude of ebb is stronger than flood (Figure 9). The tidal currents flow in the AS direction with slight drive into the CS direction. Both simulated and observed currents flow mainly southward (Figures 7 and 9), which is opposite to the poleward flow of WICC during the NE monsoon period. This indicates the study region is free from the influence of density-driven currents, but only dominated by tides.

Off Mangalore

The measured and modelled values for the CS and AS current components off Mangalore vary almost in the same range. The value ranges between –0.07 and 0.11 m/s for observed CS current, whereas the observed AS current value varies from –0.30 to 0.18 m/s and the modelled values agree, though with some discrepancies (Figure 5 *b*). Even though the nearshore currents in the eastern Arabian Sea are dominated by tides as well as local winds, the role of remote forcing cannot be ignored. This is evident while analysing the residual currents (Figure 10) off Mangalore. There is a northward-flowing residual current with a period of 4–5 days. Shetye *et al.*[41] identified the influence of remote forcing on WICC while analysing the measured currents off Goa during March and mid-April. They found that the effect of remote forcing is significant in the AS component of current. The present data off Mangalore also show similar effects, especially during the second half of April. This supports the fact that the coastal currents along the southwest coast of India are influenced by remote forcing during pre-monsoon season. The coastal circulation shows that the current flow is towards SW during ebb and towards SE during flood (Figure 11), with the ebb current slightly stronger than flood current in the region. This shows that though there is influence of northerly-flowing residual currents in the region as it is near the southern tip of India, the primary flow is towards south (Figure 7).

The predominant current system along the WCI is WICC, which flows poleward during the winter (NE) monsoon season and towards equator during the summer (SW) monsoon. However, the hydrodynamics in the shelf seas closer to the coast will not be affected significantly by density-driven currents which are dominated by tides. The winter monsoon current is density-driven, which is not considered in the present study, as the selected

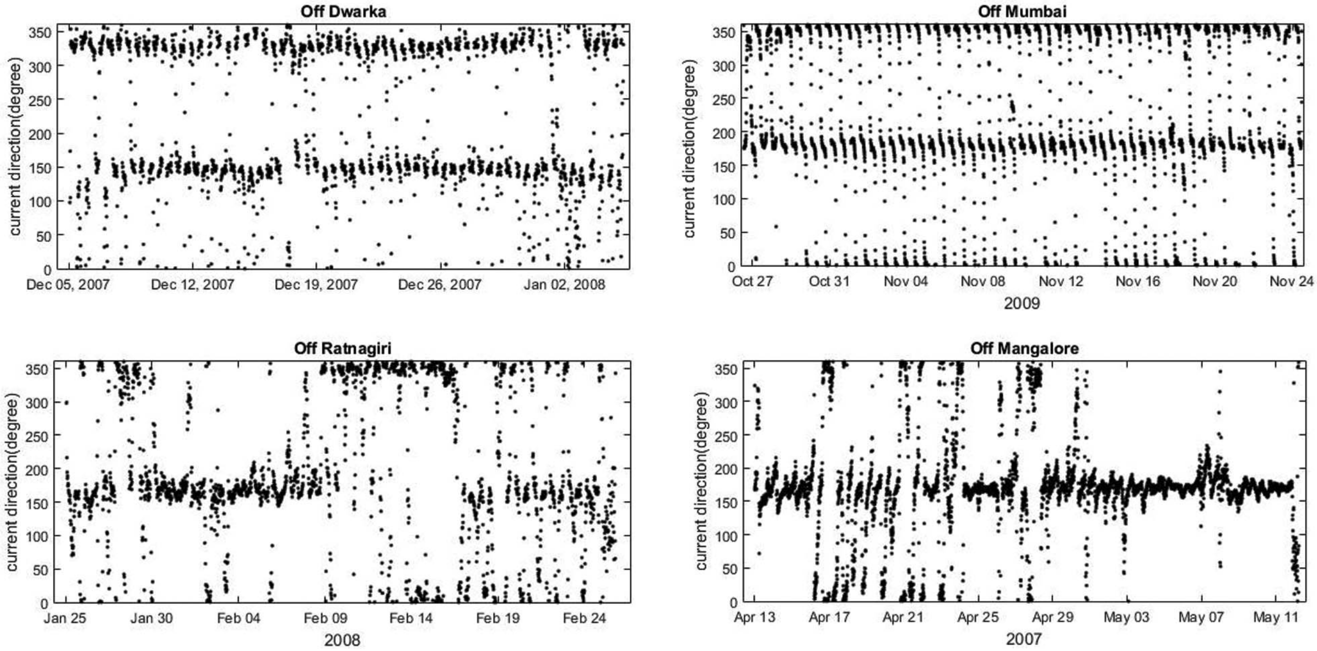

Figure 7. Observed current directions off Dwarka, Mumbai, Ratnagiri and Mangalore.

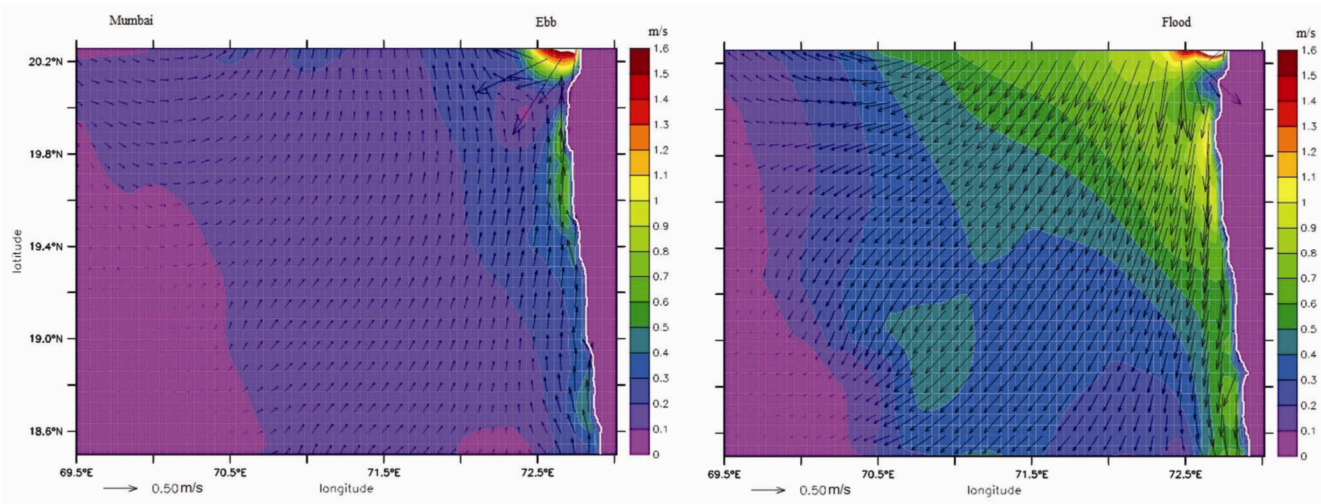

Figure 8. Simulated currents off Mumbai during ebb and flood periods.

domains are not large enough to incorporate such effects. In all the study locations it is clear that the main driving forces of the coastal current along the WCI are tides and local winds with some influence of remote residuals in the SW coast. The role of WICC may be significant along the south or southwest coast of India, since it is derived by equatorially trapped Rossby and Kelvin waves and the coastally trapped Kelvin waves generated in the Bay of Bengal propagating to the Arabian Sea after turning around Sri Lanka[42]. During NE monsoon season, the WICC reverses towards north and becomes weaker with increase in latitude[37]. The measured surface and bottom currents match well with the simulated currents in the north domains and a moderate match is noticed in the south domain which may be due to the effect of remotely arriving density-driven current. In the present study, the density effects are not considered and this may be the reason for mismatch with the observed currents. Other than this, the model results are in good agreement with the observed data.

Even though the model reproduces the observations in the study locations, detailed studies are required for analysing the circulation pattern by incorporating the temperature, salinity and flux transport. The local dynamics like meteorological inputs can be improved further with use of fine-resolution input data. The flow pattern in a

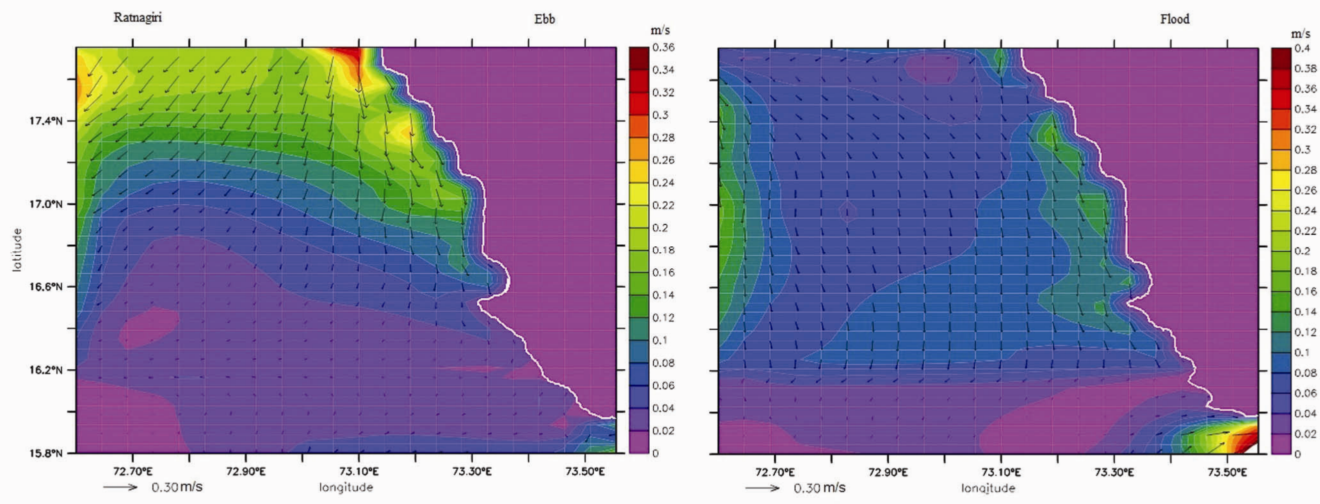

Figure 9. Simulated currents off Ratnagiri during ebb and flood periods.

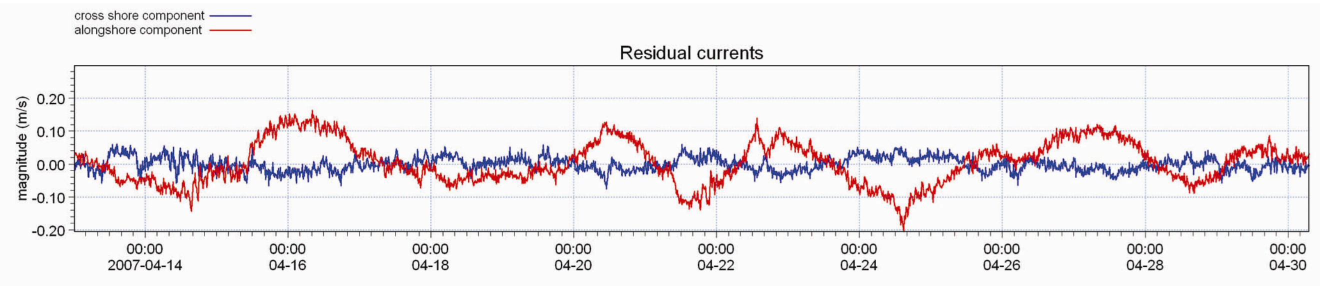

Figure 10. Cross shore and along shore residual currents off Mangalore.

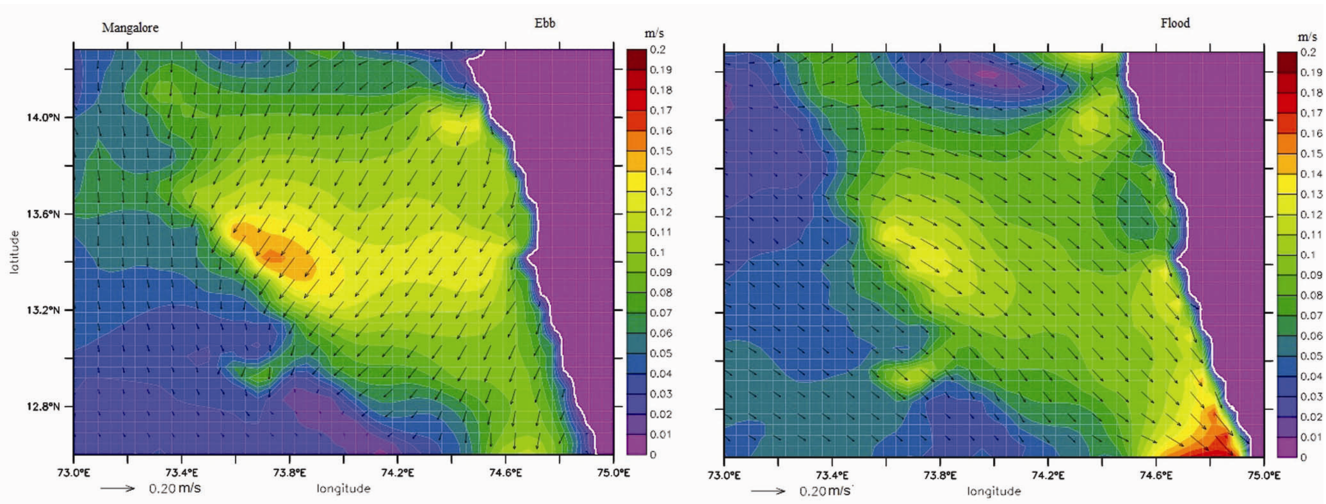

Figure 11. Simulated currents off Mangalore during ebb and flood periods.

particular region will be affected by many other factors whose influence can be studied only by considering a larger domain. The model domains considered are small, and the results can be improved by taking a larger Indian Ocean domain.

Conclusion

COHERENS is a three-dimensional multipurpose model designed exclusively for application in the coastal and shelf seas, estuaries, lakes and reservoirs. It is a freely available model which provides a detailed manual and model documentation to the user community with an active user forum. COHERENS can be applied for various scientific research studies by utilizing its multidisciplinary tasks. The hydrodynamic module can be used to study the wind-induced current and tide interactions, the baroclinic effects in the coastal seas and estuaries, and to understand the tidal propagation in the gulfs and estuaries. It can be used as an operational tide-predicting model in the coastal seas. Coupling with the biological module, it is easy to study the physical–biological interactions in the shelf seas and estuaries where the river run-off brings large amount of nutrients. The sediment transport module helps investigate the sediment plume movements, especially in the regions of large sediment deposition through river run-off during the monsoon. Lagrangian tracer module which can used for tracking both the contaminants and oil spills, may be applied for studies of wastewater management. COHERENS can also be coupled with the surface wave models like WAM and SWAN to predict the effect of meteorological parameters in the coastal seas like storm-surge. The model is more flexible and transparent because of its modular structure and the ease of selecting different processes, specific schemes and the possibility of changing the forcing parameters according to the respective applications. The programme structure is generated in such a way that the user can perform the process and predictions without detailed knowledge of the same.

COHERENS has been implemented for select locations along the WCI to generate three-dimensional barotropic currents. The numerical experiments were performed with a spatial resolution of 5 km with 20 vertical levels. The simulations were carried out over a period of one month in each location. The simulated currents have been validated with observations off four major locations along the eastern Arabian Sea shelf seas, and the match is good. This provides us the confidence to utilize the model for other regions in the WCI. The model illustrates clearly the interaction between the local winds and tidal forcing, and hence the simulation results plausibly agree with the earlier studies in these regions. The model has reproduced the coastal circulation pattern off WCI reasonably well, but needs further refinement to obtain the more accurate results, especially in the south domain where there is some effect of density-driven currents. In future, the density effect will be considered for the detailed hydrodynamic studies.

1. Kantha, L. H., Monitoring the oceans using data-assimilative models: implications for integrated *in situ* and remote observing systems. In Third Symposium on Integrated Observing Systems, Abstr., 79th AMS Annual Meeting, Dallas, TX, USA, 1999.
2. Kantha, L. H., Choi, J. K., Leben, R., Cooper, C., Vogel, M. and Feeney, J., Hindcasts and realtime nowcast/forecasts of currents in the Gulf of Mexico. In Offshore Technology Conference, Houston, TX, USA, 1999.
3. Kantha, L., Choi, J.-K., Schaudt, K. J. and Cooper, C. K., A regional data-assimilative model for operational use in the Gulf of Mexico. In *Circulation in the Gulf of Mexico: Observations and Models* (eds Sturges, W. and Lugo-Fernandez, A.), American Geophysical Union, Washington DC, 2005; doi:10.1029/161GM14.
4. McCreary Jr, J. P., Kundu, P. K. and Molinari, R. L., A numerical investigation of dynamics, thermodynamics and mixed layer processes in the Indian Ocean. *Prog. Oceanogr.*, 1993, **31**, 181–244.
5. Lee, J. Y., Tett, P., Jones, K., Jones, S., Luyten, P., Smith, C. and Wild-Allen, K., The PROWQM physical–biological model with benthic–pelagic coupling applied to the northern North Sea. *J. Sea Res.*, 2002, **48**, 287–331.
6. Marinov, D., Norro, A. and Zaldívar, J. M., Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore). *Ecol. Model.*, 2005, **193**, 52–68.
7. Luyten, P. J., Jones, J. E., Proctor, R., Tabor, A., Tett, P. and Wild-Allen, K., COHERENS – a coupled hydrodynamical–ecological model for regional and shelf seas: user documentation, MUMM Report, Management Unit of the Mathematical Models of the North Sea, 1999, p. 911.
8. Luyten, P. J., Jones, J. E. and Proctor, P., A numerical study of the long and short term temperature variability and thermal circulation in the North Sea. *J. Phys. Oceanogr.*, 2003, **33**, 37–56.
9. Obino, R., Simulation of the Bohai sea circulation and thermohaline structure using COHERENS model. M Sc thesis, Naval Postgraduate School, Monterey, CA, 2002.
10. Liang, B. C., Li, H. J. and Lee, D. Y., Numerical study of three-dimensional suspended sediment transport in waves and currents. *Ocean Eng.*, 2007, **34**, 1569–1583.
11. Lacroix, G., Ruddick, K., Gypens, N. and Lancelot, C., Modelling the relative impact of rivers (Scheldt/Rhine/Seine) and Western Channel waters on the nutrient and diatoms/*Phaeocystis* distribution in Belgian waters (southern North Sea). *Cont. Shelf Res.*, 2007, **27**, 1422–1446.
12. Guillou, N. and Chapalain, G., Modelling impact of northerly wind-generated waves on sediments resuspensions in the Dover Strait and adjacent waters. *Cont. Shelf Res.*, 2011, **31**, 1894–1903.
13. Shenoi, S. C. and Antony, M., Current measurements over the western continental shelf of India. *Cont. Shelf Res.*, 1991. **11**(1), 81–93.
14. Shetye, S., Gouveia, A., Shenoi, S., Michael, G., Sundar, D., Almeida, A. and Santanam, K., The coastal current off western India during the northeast monsoon. *Deep-Sea Res. Part A*, 1991, **38**(12), 1517–1529.
15. Rao, A. D. and Joshi, M., Modelling of upwelling processes during pre-monsoon and monsoon along the west coast of India. *Int. J. Ecol. Deve.*, 2008, **10**(S08).
16. Vethamony, P., Reddy, G. S., Babu, M. T., Desa, E. and Sudheesh, K., Tidal eddies in a semienclosed basin: a model study. *Mar. Environ. Res.*, 2005, **59**, 519–532.
17. Vethamony, P., Aboobacker, V., Sudheesh, K., Babu, M. and Kumar, K. A., Demarcation of inland vessels' limit off Mormugao port region, India: a pilot study for the safety of inland vessels using wave modelling. *Nat. Hazards*, 2009, **49**(2), 411–420.
18. Dhanya, P., Vethamony, P., Sudheesh, K., Smitha, G., Babu, M. T. and Balakrishnan Nair, T. M., Simulation of coastal winds along the central west coast of India using the MM5 mesoscalemodel. *Meteorol. Atmos. Phys.*, 2010, **109**, 91–106.
19. Babu, M. T., Vethamony, P. and Ehrlich, D., Modelling tide-driven currents and residual eddies in the Gulf of Kachchh and their seasonal variability: a marine environmental planning perspective. *Ecol. Model.*, 2005, **184**, 299–312.
20. Mandal, S., Chandramohan, P., Ranju, N. S. W. and Pathak, K. C., Ocean outfall off Mangalore, west coast of India. In International

Conference in Ocean Engineering, COE '96, IIT, Madras, Chennai, 1996, pp. 537–540.
21. Unnikrishnan, A, S., Tidal propagation off the central west coast of India. *Indian J. Geomar. Sci.*, 2010, **39**(4), 485–488.
22. Shetye, S. R., Dynamics of currents in the coastal region of India. In National Conference on Current Trends in Ocean Prediction with Special Reference to Indian Seas. Naval Physical and Oceanographic Laboratory, Kochi, 1998.
23. Banse, K., Overview of the hydrography and associated biological phenomena in the Arabian Sea, off Pakistan. In *Marine Geology and Oceanography of the Arabian Sea and Coastal Pakistan* (eds Haq, B. U. and Milliman, J. D.), Von Nostrand Reinhold, New York, 1984, pp. 271–303.
24. Clarke, A. J. and Liu, X., Observations and dynamics of semi-annual and annual sea levels near the eastern equatorial Indian Ocean boundary. *J. Phys. Oceanogr*., 1993, **23**, 386–399.
25. Madhupratap, M., Prasanna Kumar, S., Bhattathiri, P. M. A., Raghukumar, S., Nair, K. K. C. and Ramaiah, N., Mechanism of biological response to winter cooling in the northeastern Arabian Sea. *Nature*, 1996, **384**, 549–552.
26. George, G., Fish larval transport in the coastal waters through ecological modelling, Ph D thesis, Goa University, 2012.
27. Vinod Kumar, K., Aboobacker, V. M., Saheed, P. P. and Vethamony, P., Coastal circulation along the central west coast of India during cyclone Phyan: measurements and numerical simulations. *Nat. Hazards*, 2012, **64**, 259–271.
28. Kalnay, E. *et al*., The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc*., 1996, **77**, 437–470.
29. Kondo, J., Air–sea bulk transfer coefficients in diabatic conditions. *Bound.-Lay. Meteorol*., 1975, **9**, 91–112.
30. Roed, L. P. and Cooper, C. K., A study of various open boundary conditions for windforced barotropic numerical ocean models. In *Three-Dimensional Models of Marine and Estuarine Dynamics* (eds Nihoul, J. C. J. and Jamart, B. M.), Amsterdam, Elsevier, 1987, pp. 305–335.
31. Ishikawa, Y., Awaji, T., Komori, N. and Toyoda, T., Application of sensitivity analysis using an adjoint model for short-range forecasts of the Kuroshio path south of Japan. *J. Oceanogr.*, 2004, **60**, 293–301.
32. Arakawa, A. and Suarez, M. J., Vertical differencing of the primitive equations in sigma coordinates. *Mon. Weather Rev.*, 1983, **111**, 34–45.
33. Blumberg, A. F. and Mellor, G. L., A description of a three-dimensional coastal ocean circulation model. In *Three Dimensional Coastal Ocean Models, Vol. 4, Coastal and Estuarine Sciences* (ed. Heaps, N. S.), American Geophysical Union, Washington DC, 1987, pp. 1–16.
34. British Oceanographic Data Center Centenary edition of the GEBCO digital atlas [CDROM]. Published on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization, Liverpool, 2003.
35. Andersen, O., Global ocean tides from ERS-1 and TOPEX/POSEIDON altimetry. *J. Geophys. Res.*, 1995, **100**, 25, 249-25, 259.
36. Andersen, O., Woodworth, P. and Flather, R., Intercomparison of recent ocean tide models. *J. Geophys. Res.*, 1995, **100**, 25, 261-25, 282.
37. Hareesh Kumar, P. V. and Mohan Kumar, N., On the flow and thermohaline structure off Cochin during pre-monsoon season. *Cont. Shelf Res*., 1996, **16**(4), 457–468.
38. Vethamony, P. and Babu, M. T., Current and tide measurements for the design of a pipeline from Jamnagar to Kandla Route, Gujarat. Report No. NIO/SP-25/96, National Institute of Oceanography, Goa, 1996.
39. Shetye, S. R., Tides in the Gulf of Kutchchh, India. *Cont. Shelf. Res*., 2009, **19**, 1771–1782.
40. Aboobacker, V. M., Vethamony, P. and Rashmi, R., 'Shamal' swells in the Arabian Sea and their influence along the west coast of India. *Geophys. Res. Lett*., 2011, **38**(3).
41. Shetye, S. R. *et al.*, Observational evidence for remote forcing of the West India Coastal Current. *J. Geophys. Res.*, 2008, **113**, C11001.
42. Shankar, D., Vinayachandran, P. N., Unnikrishnan, A. S. and Shetye, S. R., The monsoon currents in the north Indian Ocean. *Prog. Oceanogr.*, 2001, **52**, 63–120.

ACKNOWLEDGEMENTS. We thank the Director, National Institute of Oceanography, Goa for providing the necessary facilities and P. Luyten (Management Unit of the North Sea Mathematical Models, Brussels, Belgium) for providing the COHERENS model. The field data were collected under the project 'Waste assimilative capacity of select Indian coastal waters', funded by the ICMAM/MoES, Chennai. B.J. acknowledges The Brazilian National Council for Scientific and Technological Development (CNPq Procs. 490806/2007–4 and 490222/2011-0) for funding and training at The University of São Paulo. This is NIO contribution no. 5774.

Received 10 September 2014; revised accepted 20 April 2015