Numerical Modeling of Surface and Near Bottom Currents in the Bushehr Bay

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Abstract
Bushehr Bay is situated along the northern Iranian coasts of the Persian Gulf, between 28°52’ and 29°5’ north latitude and 50°42’ and 50°52’ east longitude. In this study COHERENS, which is a three-dimensional hydrodynamic model was employed to simulate surface and under surface currents in the Bushehr Bay. The atmospheric forces and four main tidal constituents M2, S2, K1, O1 and also boundary forces were applied in the model. The simulation results and observations showed that the current in the Bushehr Bay was dominated by tide-driven currents.

Keywords: Flood currents, Ebb currents, Seasonal currents, Bushehr Bay, Persian Gulf.

1. Introduction

The characteristics of coastal waters differ in many aspects from those of the open sea. Some of the factors causing these differences are tidal currents, river run off, and the effect of shore boundaries on the circulation. The effect of the shore as a boundary in limiting possible directions of flow is considerable.

The effects of tidal currents depend on the tidal behavior of a region can be two fold. They may cause large changes twice daily in the volume of water in a harbor or bay and also may promote vertical mixing and thus, break down the stratification in water.

In this study, to quantify the currents in a shallow tide-affected bay (Bushehr Bay), a three-dimensional hydrodynamic model of COHERENS was employed. Bushehr Bay is situated along the north Iranian coasts of the Persian Gulf and the northern side of Bushehr Peninsula. The bay is located between 28°,52’ N to 29°,5’ of N (~ 25km) latitude and between 50°,42’E to 50°,52’E (~ 17km) longitude, (Fig. 1).

Fig. 1: The position of the Bushehr Bay in the Persian Gulf.

The east and north boundaries of the bay extend to
Shif island and the lowlands of Bushehr, respectively. In the southeast boundary, Bushehr Seaport connects this bay to Soltani and Lashgari estuaries, while the west and southwest boundaries of the Bushehr bay reach the Persian Gulf, (Fig. 2). Deeper area with greater than 20m depths is found along the southwest corner in the Persian Gulf. The maximum depth of the Bay is 26 m.

Sadrinasab and Kaempf (2004) investigated the flushing times of the Persian Gulf using COHERENS model. The results of the model showed that 95% flushing times of surface waters were shortest (1–3 yrs, increasing with distance from the Strait) along the Iranian coast, but were much longer (>5 yr) along the coasts of Kuwait and Saudi Arabia. Owing to density stratification introduced by the surface inflow of ocean water, flushing times of bottom waters are estimated to be 6 yr in most parts of the Persian Gulf.

Kaempf and Sadrinasab (2005) employed COHERENS model to study the circulation and water mass properties of the Persian Gulf. Their findings suggested that the Persian Gulf experienced a distinct seasonal cycle in which a Gulf-wide cyclonic overturning circulation is established in spring and summer, but is disintegrated into mesoscale eddies in autumn and winter. Establishment of the Gulf-wide circulation coincided with establishment of thermal stratification and strengthening of the baroclinic exchange circulation through the Strait of Hormuz.

COHERENS model was also employed by Kaempf (2007) to derive the magnitude of on-shelf fluxes through a shelf-break canyon for a wide range of canyon sizes and ambient oceanic conditions. Predicted canyon-upwelling fluxes are of the order of 0.05–0.1 Sv (1 Sv = 1 million m³/s), being several orders of magnitude greater than upslope fluxes in the bottom Ekman layer on the ambient continental slope. For typical conditions, the upwelling flux varies quadratically with forcing strength (speed of incident flow), linearly with canyon depth, and is inversely proportional to the buoyancy frequency of the density stratification inside the canyon.

Bingchen et al. (2008) used SWAN and COHERENS models to stimulate and predict hydrodynamic and contaminant conditions under wave and current interaction in Yangpu bay. SWAN is introduced into COHERENS as a subroutine. COHERENS gets wave height, period and direction through calling SWAN. SWAN gets current velocity and surface elevation from COHERENS to account

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*Fig. 2: The positions of Bushehr Seaport, Shif Island and the status of access channels to this port.*

The dominant wind in the region of study is northwesterly which is called Shamal by local people (Clark, 1982). According to tide tables and field measurements, tidal type in this region is mixed tide and mainly semidiurnal (Fig. 3). Highest high water is about 2 meters, but under strong westerly winds, it increases to about 2.7 m (JWERC, 2000).

*Fig. 3: Monthly changes of water level in Bushehr Bay (JWERC, 2000).*

This study could potentially make a foundation for the other local hydraulic and hydrodynamic studies. It should be noted that the application of COHERENS has been mentioned before by some studies.
for their effects on wave simulation. The simulation results of flow and surface levels agree with measurement in terms of 8 current observation stations and 2 surface level stations. The fields of current velocity and contaminant concentration obtained from modeling of case with wave-induced longshore current are different obviously.

Using COHERENS model, Hassanzadeh et al. (2010) showed the salinity in the Persian Gulf experienced dramatic spatial and temporal variations. The influence of the thermohaline forcing was considerably greater than the wind stress on the salinity. The effect of the surface thermohaline fluxes over the salinity field was generally to increase the salinity for almost all the water column during the year.

Mahmoudov et al. (2011), used COHERENS model to simulate currents in the Qeshm Channel, a shallow and narrow waterway located between Qeshm Island and the mainland in the vicinity of Hormuzgan Province, I. R. Iran. Simulation of currents was carried out in 20 sigma levels from the seabed to the water surface during one month and very good agreements were found between the numerical results and the field data recorded by the experts from Iranian National Center for Oceanography.

2. Methods

The hydrodynamics model of COHERENS (Coupled Hydro dynamical Ecological model for REgioNal Shelf seas) (Luyten et al., 1999), which is based on a bottom following vertical sigma coordinate system was used. The basic equations for the three-dimensional model (Gill, 1982) are:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x_1} + v \frac{\partial u}{\partial x_2} + w \frac{\partial u}{\partial x_3} = -\frac{1}{\rho_0} \frac{\partial p}{\partial x_1} + \frac{1}{\rho_0} (\nu_T \frac{\partial u}{\partial x_3}) + \frac{1}{\rho_0} \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3}) + \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3}) + \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3})
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x_1} + v \frac{\partial v}{\partial x_2} + w \frac{\partial v}{\partial x_3} + f v = -\frac{1}{\rho_0} \frac{\partial p}{\partial x_2} + \frac{1}{\rho_0} (\nu_T \frac{\partial v}{\partial x_3}) + \frac{1}{\rho_0} \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3}) + \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3}) + \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3})
\]

\[
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x_1} + v \frac{\partial w}{\partial x_2} + w \frac{\partial w}{\partial x_3} + f u = -\frac{1}{\rho_0} \frac{\partial p}{\partial x_3} + \frac{1}{\rho_0} (\nu_T \frac{\partial w}{\partial x_3}) + \frac{1}{\rho_0} \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3}) + \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3}) + \frac{\partial}{\partial x_3} (\frac{\nu_T}{\partial x_3})
\]

where \((u, v, w)\) are the components of the current, \(T\) denotes the temperature, \(S\) the salinity, \(f = 2\Omega \sin \varphi\) the Coriolis frequency, \(\Omega = 2\pi/86164\) rad/s the rotation frequency of the Earth, \(g\) the acceleration of gravity, \(p\) the pressure, \(\nu_T\) and \(\lambda_T\) the vertical eddy viscosity and diffusion coefficients, \(\lambda_H\) the horizontal diffusion coefficient for salinity and temperature, \(\rho\) the density, \(\rho_0\) a reference density, \(c_p\) the specific heat of seawater at constant pressure and \(I(x_1, x_2, x_3, t)\) solar irradiance. The horizontal components of the stress tensor are defined by:

\[
\tau_{11} = 2 \nu_H \frac{\partial u}{\partial x_1}
\]

\[
\tau_{12} = \tau_{21} = \nu_H \left( \frac{\partial u}{\partial x_2} + \frac{\partial v}{\partial x_1} \right)
\]

\[
\tau_{22} = 2 \nu_H \frac{\partial v}{\partial x_2}
\]

Where \(\nu_H\) is the horizontal diffusion coefficient for momentum.

To determine turbulence scheme and in analogy with molecular diffusion where the eddy viscosity and diffusion coefficients are proportional to the mean velocity times the mean free path of the molecules, the eddy coefficients \(\nu_T\) and \(\lambda_T\) are considered as the product of a turbulent velocity scale and a length scale \(l\) usually denoted by the Kolmogorov-Prandtl “mixing length”. A commonly used velocity scale is the square root \(kl/2\) of the turbulent kinetic energy (Xing and Davies, 1996).
the eddy viscosity and diffusion coefficients ($\nu_T$, $\lambda_T$), are then expressed as:

$$\nu_T = S_m k^{1/2} l + \nu_b$$

$$\lambda_T = S_h k^{1/2} l + \lambda_b$$

Where $k$ and $l$ are turbulent kinetic energy and mixing length, respectively. $S_m$, $S_h$ are usually referred as the stability functions and $\nu_b$, $\lambda_b$ are prescribed background coefficients (Burchard and Baumert, 1995).

The model uses discrete equations in horizontal planes, the Arakawa C-grid (Arakawa and Suarez, 1983), and finite difference method.

The short wave radiative flux is calculated on an hourly basis to resolve its diurnal variation. Atmospheric conditions are assumed to be uniform in space but variable in time. A quadratic bulk formula is used to calculate surface frictional stresses with a wind-dependant formulation of the drag coefficient proposed by Geernaert et al. (1986).

A mode-splitting technique is employed to maximise model performance. A predictor corrector method is used to solve the horizontal momentum equations. This satisfies the requirement that, when using a mode-splitting technique of solution, the currents in the three-dimensional equations should have the same depth integral as the ones obtained from the two-dimensional, depth integrated equations (Blumberg and Mellor, 1987). The TVD (Total Variation Diminishing) scheme using the super bee limiter as a weighting function between the upwind scheme and either the Lax-Wendroff scheme in the horizontal or the central scheme in the vertical is used to represent advection of scalars such as temperature and salinity. A simple upstream scheme was used for momentum advection. All horizontal derivatives were evaluated explicitly while vertical diffusion was computed fully implicitly and vertical advection quasi-implicitly. Forward-backward interpolation of the Coriolis term was implemented (Sielecki, 1968).

In this application, we used time steps of barotropic and baroclinic modes of 36 s and 6 s, respectively, which satisfied stability criteria associated with external and internal wave propagation, advection, and hydrostatic consistency (Mesinger and Janjic, 1985). This model was run in a fully prognostic mode with Cartesian lateral coordinates on the f plane, using geographical latitude of $29^\circ$ N.

Data assimilation methods (other than prescription of boundary data) were not employed. Further details of numerical techniques employed in the COHERENS model could be taken from Luyten et al., (1999).

Bathymetry of the study area with lateral grid spacing of $\Delta x=\Delta y=250 m$ (east-west direction and north-south direction) was employed into the model (Figure 4) with 10 sigma levels ($\sigma = 0$ for near bottom level and $\sigma = 1$ for near surface level). Domain’s bathymetry is based on navigational chart data (1997) modified by British Hydrographic Office in 2010. It, in addition, has been interpolated and slightly smoothed onto a 250 meters grid.

![Fig. 4: Bathymetry of the Bushehr Bay; applied in the model.](image)

Daily mean of atmospheric parameters of Bushehr marine meteorological station in a 40-year statistical period (1968-2008) including wind speed (W S), wind direction (W D), air temperature (A T), relative humidity (H), evaporation (E), precipitation (P) and cloud cover (C) were used in the model.

Table 1 shows monthly mean of the atmospheric parameters (AMRCB, 2008).
Table 1. Monthly mean of atmospheric parameters of Bushehr marine meteorological station in a 48 year statistical period (1968-2008).

<table>
<thead>
<tr>
<th>Month</th>
<th>W (m/s)</th>
<th>S (deg)</th>
<th>T (°C)</th>
<th>H (%)</th>
<th>E (mm)</th>
<th>P (mm)</th>
<th>C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>3.2</td>
<td>329.6</td>
<td>14.6</td>
<td>74.2</td>
<td>3.39</td>
<td>2.79</td>
<td>40</td>
</tr>
<tr>
<td>Feb</td>
<td>3.5</td>
<td>316.4</td>
<td>15.9</td>
<td>70.9</td>
<td>4.01</td>
<td>1.12</td>
<td>49.5</td>
</tr>
<tr>
<td>Mar</td>
<td>3.8</td>
<td>301.6</td>
<td>19.1</td>
<td>67.2</td>
<td>5.13</td>
<td>0.73</td>
<td>59.9</td>
</tr>
<tr>
<td>Apr</td>
<td>4.7</td>
<td>299.7</td>
<td>24.1</td>
<td>62.2</td>
<td>6.99</td>
<td>0.21</td>
<td>51.4</td>
</tr>
<tr>
<td>May</td>
<td>6.3</td>
<td>302.6</td>
<td>28.9</td>
<td>57.6</td>
<td>9.41</td>
<td>0.06</td>
<td>49.5</td>
</tr>
<tr>
<td>Jun</td>
<td>6.5</td>
<td>300.3</td>
<td>31</td>
<td>60.9</td>
<td>10.19</td>
<td>0.00</td>
<td>50.1</td>
</tr>
<tr>
<td>Jul</td>
<td>5.3</td>
<td>280.2</td>
<td>32.6</td>
<td>64.6</td>
<td>9.70</td>
<td>0.00</td>
<td>50</td>
</tr>
<tr>
<td>Aug</td>
<td>5.6</td>
<td>88.3</td>
<td>32.9</td>
<td>66.9</td>
<td>9.23</td>
<td>0.01</td>
<td>49.8</td>
</tr>
<tr>
<td>Sep</td>
<td>5.6</td>
<td>280.5</td>
<td>30.8</td>
<td>65.8</td>
<td>8.50</td>
<td>0.00</td>
<td>29.7</td>
</tr>
<tr>
<td>Oct</td>
<td>5</td>
<td>295.9</td>
<td>27.2</td>
<td>64.5</td>
<td>7.11</td>
<td>0.25</td>
<td>30.5</td>
</tr>
<tr>
<td>Nov</td>
<td>4.1</td>
<td>320.1</td>
<td>21.6</td>
<td>64.5</td>
<td>5.29</td>
<td>1.15</td>
<td>30.1</td>
</tr>
<tr>
<td>Dec</td>
<td>3.1</td>
<td>337</td>
<td>16.8</td>
<td>72.2</td>
<td>3.78</td>
<td>2.46</td>
<td>30</td>
</tr>
</tbody>
</table>

We applied the simulated daily mean temperature and salinity of another model (Kaempf and Sadrinasab, 2005), in the Persian Gulf for temperature and salinity in the open boundaries of this study. These input data agreed with the monthly hydrographic observations of Alessi et al. (1999). Monthly mean of temperature and salinity in the open boundaries is presented in Table 2.

Table 2. Monthly mean upper-ocean salinity (psu) and temperature (°C) values at the open boundaries (Kaempf and Sadrinasab, 2006).

<table>
<thead>
<tr>
<th>Month</th>
<th>Salinity (psu)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>39.98</td>
<td>20.73</td>
</tr>
<tr>
<td>Feb</td>
<td>40.05</td>
<td>19.94</td>
</tr>
<tr>
<td>Mar</td>
<td>40.12</td>
<td>20.42</td>
</tr>
<tr>
<td>Apr</td>
<td>40.17</td>
<td>21.41</td>
</tr>
<tr>
<td>May</td>
<td>40.20</td>
<td>22.20</td>
</tr>
<tr>
<td>Jun</td>
<td>39.97</td>
<td>25.24</td>
</tr>
<tr>
<td>Jul</td>
<td>39.62</td>
<td>27.00</td>
</tr>
<tr>
<td>Aug</td>
<td>39.56</td>
<td>27.79</td>
</tr>
<tr>
<td>Sep</td>
<td>39.52</td>
<td>28.22</td>
</tr>
<tr>
<td>Oct</td>
<td>39.59</td>
<td>27.60</td>
</tr>
<tr>
<td>Nov</td>
<td>39.77</td>
<td>25.92</td>
</tr>
<tr>
<td>Dec</td>
<td>39.94</td>
<td>23.35</td>
</tr>
</tbody>
</table>

Moreover, amplitudes and phases of four main tidal components (M₂, S₂, O₁ and K₁), were applied to the open boundaries of the model (Table3).

Table 3. Tidal components of Bushehr seaport were applied to the model (Foreman, 1977).

<table>
<thead>
<tr>
<th>tidal component</th>
<th>M₂</th>
<th>S₂</th>
<th>O₁</th>
<th>K₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude of tidal component (m)</td>
<td>0.34</td>
<td>0.12</td>
<td>0.2</td>
<td>0.31</td>
</tr>
<tr>
<td>phase of tidal component (Ra)</td>
<td>3.68</td>
<td>4.62</td>
<td>4.15</td>
<td>4.88</td>
</tr>
</tbody>
</table>

3. Results and Discussion

Total simulation of 5 years is for run in a fully prognostic mode. This time is sufficiently long for representing a steady-state seasonal cycle of circulation and water mass properties in the Bushehr Bay.

Figure 5 illustrates the steady state of the annual cycle of average temperature and salinity of of depth in the study region for past two years of simulation as depicted by the model.

![Figure 5: Time series of vertical-averaged of temperature (°C), and salinity (psu), for the last two years of simulation.](image)

Results of the model presented in this paper are derived from the final year of the selected 5-year simulation study and agreed strongly with observational evidence.

Measured (JWERC, 2000), 14 days tidal levels, current’s magnitude and direction of current at location A (fig. 4) are compared with the computed values by the model, respectively (Figs. 6, 7 and 8)*.

Water level fluctuations (tide) were measured by automatic water level recorder (pressure sensor type) every 15-minutes. Current velocity and direction were recorded in average depth by automatic propeller current meters every 5-minutes.

![Figure 6: Comparison of sea surface elevation (tide), obtained from measurement (JWERC, 2000), with the model at location A.](image)
The simulated performance was evaluated using a goodness of fit measures, namely the Correlation Coefficient (Prasertsak et al., 2010):

$$\text{Correlation Coefficient} = \frac{\sum_{i=1}^{N}(O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2 \sum_{i=1}^{N}(S_i - \bar{S})^2}}$$

Where: \(N\) is the total number of data, \(O_i\) is the measured data and \(S_i\) is the simulated data. Also \(\bar{S}\) and \(\bar{O}\) are their corresponding mean value. In ideal conditions, the Correlation Coefficient value closer to 1 indicated the model displayed greater accuracy.

Correlation Coefficient of tidal levels, current magnitude and direction of current were 0.83, 0.67 and 0.75, respectively. So, the results of the model were in good agreement with data of observations.

In another field measurement, the directions of flood and ebb currents were recorded with floats during high tide and low tide (Figs. 9 and 10). During flood current, floats moved with the currents along the outer channel, were directed towards north and north-east and mainly into the Soltani estuary. During ebb currents, however, floats moved from coast of Shif island and inner channel towards sea parallel to outer channel.

Figure 11, shows fluctuation of water level and current magnitude obtained from the model and measurement data during a tidal period at the Bushehr bay. According to figure 11, during low
water slacks (times A and C in Fig. 11) and high water slacks (times B and D in Fig. 11) current speed is reduced to its minimum values. At these times, the direction of current changed from ebb to flood and vice versa.

During flood, when water level increased from A to B water moved into the Gulf from surface to bottom (Figures 12a, b).

Also, when water level decreases from B to C water moves out of the Gulf from surface to bottom (Figures 13a, b).

Fig. 11: water level fluctuations and current speed obtained from model and measurement data (JWERC, 2000), during a complete tidal cycle.

Fig. 12a : Average surface flood current during times A to B obtained from model.

Fig. 12b: Average bottom flood current during times A to B obtained from model.

Fig. 13a: Average surface ebb current during times B to C obtained from model.

Fig. 13b: Average bottom ebb current during times B to C obtained from model.

Comparison of figure 12.a with figure 9 and figure 13.a with figure 10, show that trajectories of the floats fully comply with the direction of currents of the model.

To ensure compliance of model results and measurements, mean seasonal current patterns were predicted in the Bushehr Bay.

Figures 14 and 15 show average surface and bottom currents in summer and winter, respectively. During summer, surface currents often are influenced by wind while, bottom currents mostly influenced by difference of density. Meanwhile, in estuaries, surface current flows into the estuaries and bottom
current flows out of the estuaries (Figures 14a, b).

Fig. 14a: Average surface currents during summer obtained from model.

Fig. 14b: Average bottom currents during summer obtained from model.

During winter, surface currents are also influenced by wind while, bottom currents are very weak (Figures 15a, b).

Fig. 15a: Average surface currents during winter obtained from model.

Fig. 15b: Average bottom currents during winter obtained from model.

In order to survey the currents in the Soltani estuary (between $y_1$ and $y_2$ points, figure 4) more precisely, a perpendicular portion was selected at its entrance. Figures 16 and 17 show the vertical profiles of average flood and ebb currents for 10 sigma levels in two points of the Soltani estuary mouth. Also, the profiles of average currents during summer and winter are presented in figures 18 and 19.

Fig. 16: Vertical profile of average flood current in perpendicular portion of Soltani estuaries’ mouth.

Fig. 17: Vertical profile of average ebb current in perpendicular portion of Soltani estuaries’ mouth.
4. CONCLUSION

The present modeling study showed that current pattern in Bushehr Bay varied in time and vertical sigma levels from surface to bottom. Currents were different from one point to other, and the field measurements showed a similar variation.

This study compared the current patterns for a 14-day period and investigated the whole bay for high and low tides durations as well as for different seasons. The following results were obtained:

1- The results of the model and measurements showed that currents were induced intermittent by tides. Therefore, the amplitudes of water level and current magnitude increased and decreased when spring tide and neap tide occur, respectively.

2- Correlation Coefficients of sea surface elevation (tide), obtained from model and that taken from measurements were calculated as 0.83. On the other hand, it was 0.67 for current magnitude of model and measurements and 0.75 for current direction.

3- The flood and ebb currents near and away from the coasts are different. The currents pattern in the Bushehr Bay showed that flood and ebb currents were northward and southward, respectively.

4- In vertical levels, the flood current flows into the Soltani estuary and ebb current flows out of the estuary.

5- The least values of current magnitudes occurred at the moments of maximum and minimum water level fluctuations as the slack water times.

6- Seasonal surface currents were often induced by dominant wind and seasonal bottom currents mostly under- influenced by difference of density.

7- In the seasonal current patterns, if surface currents approached the coast, bottom currents left there and vice versa. It could indicate the reliability and accuracy of this model. Since, once surface and bottom seasonal currents symmetrically occur near the coast, either accumulation of water or desiccation of coast would take place.

8- An important feature of seasonal currents in Bushehr estuaries was that the surface current flowed into the Soltani estuary and bottom current flowed out of the estuary.

Acknowledgments

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