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Numerical study of water circulation in Persian Gulf using finite difference method

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Abstract

The Persian Gulf region is of great importance for economic and political reasons, which is due to oil resources and marine exports in the region. The dominant geophysical phenomenon that affects on the water flow in the area is the seasonal winds that blow from the African coast toward the Red Sea and influence all the coast line of Persian Gulf and reach to the India from the east. Other important and effective factors in the water circulation of the region are the net evaporation of about two meters per year, high density, and the rivers that flow into the Gulf. This paper investigated various factors effective on the circulations in the Persian Gulf, and then the initial governing equations were converted into the numerical equations. The equations were solved for each node in the grid network of the Persian Gulf. Using numerical methods, the current velocities and their respective directions were calculated. Finally, investigating the flow conditions in multi-layers, the velocity of water flow in different sections was studied. The results indicated the existence of circulating cells in the Persian Gulf. This circulation showed significantly reduction with depth.

Keywords: Persian Gulf; Numerical model; Current; Circulation; Evaporation.

1. Introduction

The Persian Gulf with an area of 237,473 km^2 is the third largest gulf around the world after the Gulf of Mexico and the Hudson Bay. The length of the Gulf is about 805 km and is known as the warmest part of the world. High water salinity and the diversity of fresh springs in the bottom and coasts of the Persian Gulf such as Arvand, Diyaleh, Mond, Dalaki, and Minab rivers and various winds like the North wind, Nashi wind, Kush wind, and Soheily wind with the tides are the causes of the complex water circulation in different seasons in the area.Iran has approximately 1700 km of sea border in the south, and by the Strait of Hormuz with about

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60 km wide is related to the Oman Sea and Indian Ocean. Some of the studies carried out in this area are as follows:

Scott in 1981 developed his observations on the Persian Gulf from the ships (Johns and Jacobs, 1999), and Emery in 1956 published some surface maps and profiles related to the distribution of temperature and salinity in the Persian Gulf (Hunter, 1982). Von Trepka in 1968 stated that the Persian Gulf is a shallow continental plateau, and the evaporation is considerably more than precipitation (Chao *et al.,* 1990). The average annual heat flux of the Persian Gulf was calculated by the evaporation of 168 W/m^2 (Ahmad and Sultan, 1990). Furthermore, Density is probably the most dominant factor in the long run circulation in the Persian Gulf (Hunter, 1982).

He also stated that tidal fluctuation is small (Hunter, 1983). The Persian Gulf region was investigated by Grassho in 1976 and Hunter (1982) from physical point of view. And more comprehensive studies of the area were carried out by Purser in 1973 and UNESCO in1976. In other research in the Persian Gulf, Khaleghi Zavareh (1992) introduced a non-linear two-dimensional numerical barotropic model. In this model, the shallow water equations are discussed with regard to the effects of Earth rotation, bottom friction, and wind and tidal forces, by numerical simulation.

The Mount Mitchell survey vessel began a 100-day trip in March 1991included six round trips in the Persian Gulf. During the first and sixth rounds, the entire Persian Gulf and coastal zone of Iran, and in the third round was exclusively in the coasts of Iran, and the other rounds were on the Arabian coasts. The research outcomes are represented as follows (Pieehura and Walczowski, 1993). In the winter, the movement of waves toward the coastline of Iran increase due to the northwest winds (shamal), and in the summer, these winds are caused the currents intensity increasement (Khalil Abadi *et al.,* 2003).

The main causes of sea level changes in the northern basin of Persian Gulf are tides and atmospheric factors, so that the prevailing tide in this area is mainly half-day tide, and because of low atmospheric pressure mainly entered from the northwest to the Persian Gulf, so the storm surge moves along the northern coasts of the Persian Gulf from west to east (Khalil Abadi *et al.,* 2004). Rashidi et al. (2006) used a three-dimensional model in a spherical coordinate system with a hyphenated Sigma array. Solving equations also used a finite difference numerical method. Banazadeh et al. (2002) analyzed a three-dimensional flow model and a survey of flow conditions in several layers and investigated the velocities and temperatures.

2. Materials and methods

Data includes depth information, wind model, tidal information, salinity, density, air and water temperature, and the wave information contains height, period, and direction with a 6-hour interval and other information by CTD in different stations were gathered from buoys, synoptic stations and satellites.

The information were used in this research on the boundary network nodes such as river entrances are wind components in horizontal and vertical directions at a distance of 10 m above sea level, roughness, pressure with 6-hour time interval within a year. The wind data over the Persian Gulf were obtained from different stations including Kish Island, Bushehr, Abu Musa, Dayyer, Kangan, Abadan, and Bandar

Lengeh, and also over the Hormuz Strait from Qeshm station, and over the Oman Sea from Jask, Konarak, and Chabahar stations.

The used final gridding was considered as irregular triangular elements and except for the points of input and output flows, the components of velocity were assumed to be zero at the boundaries. On the surface, the stress and the heat flux were specific and at the bottom the heat flux were defined zero.

The used physical approximation and the boundary conditions are as follows:

1. Density is approximated by a second-order temperature function.
2. The variation of density in the vertical direction was neglected and the Boussincsq approximation was used. The average monthly wind stress and their direction were derived using the results of Chao study in the Persian Gulf (Chao *et al.,* 1990).
3. The 10-year meteorological data was considered as a daily average, and the four main tidal modes M2, S2, K1, and O1 were applied in the model.
4. Hydrostatic approximation was established and the vertical acceleration was neglected (Brewer *et al.,* 1985).
5. The surface was divided into three layers.
6. At the bottom of the sea, the condition of u = v = 0 was considered (Zamanian, 1994)
7. At the water surface and the bottom of Persian Gulf it was assumed that $\frac{dP}{dt}=0$.
8. At the bottom of the Persian Gulf, the stress was calculated with a linear rule, τb = ρrv (Kamenkovich *et al.,* 1996).
9. Except at the entrance and existence of the rivers, at the boundaries, the velocity components were zero.
10. The surface acts as a hard edge.

Assuming that the water in Persian Gulf is incompressible and the Boussincsq approximation is true, and the momentum is calculated as follow (Apel, 1990).

$$\frac{dU}{dt}=\frac{\partial u}{\partial t}+u.\nabla u=-2\Omega\times u-\nabla\varphi-\frac{1}{\rho}\nabla P+\frac{1}{\rho}\nabla.A.\nabla u \qquad (1)$$

In equation (1), the first term, $\frac{\partial u}{\partial t}$, is the acceleration at a fixed point, which is called the inertial sentence. The second term, u.∇u, is a nonlinear transmission sentence that represents the changes of velocity along a path. The third sentence is 2Ω×u, is the Coriolis acceleration, and the fourth sentence, ∇φ, is the integration of gravity and centripetal accelerations, and the fifth sentence $\frac{1}{\rho}\nabla P$ is the integration of the adhesion reduction and vortices effects, that is the friction term.

The thermodynamic energy equation is written as follows:

$$\frac{\partial T}{dt}=-\partial(uT)/\partial x-\partial(VT)/\partial y-\partial/\partial Z[WT-K\partial T/\partial z] \qquad (2)$$

which, T is the temperature, u, v, and w are the water flow velocity in the x, y, and z directions (Pedlosky, 1987).

Writing the Equation (1) in the X and Y directions, and calculating derivations of $\frac{-\partial}{\partial y}$ in Y in Y direction and $\frac{\partial}{\partial x}$ in X direction, and combining them is as the following formula:

$$\frac{d}{dt}\left[\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right]=-f\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)-\frac{\partial f}{\partial y}v+\frac{1}{\rho}\left[\frac{\partial^2 P}{\partial x\partial y}-\frac{\partial^2 P}{\partial x\partial y}\right] \qquad (3)$$
$$+k_h\left[\frac{\partial}{\partial x}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\frac{\partial}{\partial y}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)\right]+\frac{1}{\rho}\frac{\partial}{\partial x}\left(\frac{\partial\tau_{zy}}{\partial z}\right)-\frac{1}{\rho}\frac{\partial}{\partial y}\left(\frac{\partial\tau_{zx}}{\partial z}\right)$$

Because of using the f-plate approximation $\frac{\partial f}{\partial y}$ can be neglected. The stress-induced friction consists of two parts: the friction between wind and water surface that causes the movement of water, and the friction due to moving water over bottom that opposes the movement of water, and it prevents the movement of water, so it can be written as:

$$\tau_{y} = \tau_{sy} - \tau_{by} \tag{4}$$

$$\tau_{x} = \tau_{sx} - \tau_{bx} \tag{5}$$

$$\tau_{sx} = C_D P_a |v_{10}| u_{10}$$
$$\tau_{sy} = C_D P_a |v_{10}| u_{10} \tag{6}$$

which, U_{10} and V_{10} are the wind speed in 10-m height of the water surface in x and y directions, and C_D is the drag coefficient.
Assuming $\frac{\partial \tau_{sy}}{\partial x} + \frac{\partial \tau_{sx}}{\partial y} = \nabla \times \tau_s$ and $\frac{\partial \tau_{by}}{\partial x} + \frac{\partial \tau_{bx}}{\partial y} = \nabla \times \tau_b$ (7) , and replacing Equations of (4) to (7) in the main equation (Equation 3) and integrating from the resulted equation from the surface to the bottom, and also considering $u = \frac{-\partial \psi}{\partial y}$ and $v = \frac{\partial \psi}{\partial x}$, the following equation is obtained:

$$\frac{\partial}{\partial t}\left[\nabla^2 \Psi\right] = -u\frac{\partial}{\partial x}\left[\nabla^2 \Psi\right] - v\frac{\partial}{\partial y}\left[\nabla^2 \Psi\right] - w\frac{\partial}{\partial z}\left[\nabla^2 \Psi\right]$$
$$+k_h \nabla^4 \Psi + \frac{1}{PH}\left[(\rho_a |v_{10}| \left(\frac{\partial v_{10}}{\partial x} - \frac{\partial u_{10}}{\partial y}\right)\right] - \frac{r}{H}\nabla^2 \Psi + \frac{1}{H^2}$$
$$\left[\left(\frac{C_o \rho_a |v_{10}| u_{10}}{\rho} + r\frac{\partial \Psi}{\partial y}\right)\frac{\partial H}{\partial y} - \left(\frac{C_D \rho_a |v_{10}| v_{10}}{\rho} + r\frac{\partial \Psi}{\partial x}\right)\frac{\partial H}{\partial x}\right] \tag{8}$$

This equation is solved with the initial and boundary conditions of the Persian Gulf. Considering the existing wind-rose diagrams, the monthly average of the wind speed values and their directions are calculated, and estimated for the total annual flow. In the northern-half of the Persian Gulf, the coastal jets are directly toward the southeast of Iran coasts, and as the average wind speed decreases during the summer, this coastal jet will be almost disappeared (Lardner *et al.,* 1993).
Using the data obtained from Hormozgan Fisheries Organization, the averages of annual flow rate of rivers' intake are calculated, and the steady-flow generated by each of these averages is considered as the initial conditions.

2.1. Solving equations

In the numerical solution, the Equation (8) is used to obtain the stream function Ψ and horizontal velocity components. The problem is investigated neglecting the nonlinear terms. Since the time factor is involved in the problem, the appropriate time step must be selected for solving the problem. The maximum time step for solving the equilibrium interval is obtained from the Couran-Friedrichs- Lexy equation (O'Brien, 1986):

$$\Delta t \langle \frac{\Delta X}{(2gh_{\max})^{1/2}} \tag{9}$$

Using the value of Ψ in the next step (n + 1), the equation is obtained as follows:

$$\frac{1}{d^2\Delta t}\left[\psi_{i-1,j^{n+1}} - \psi_{i+1,j} + \psi_{i-1,j^{n-1}} - \psi_{i-1,j} + \psi_{i^{n+1},j-1} - \psi_{i,j+1} + \psi_{i^{n+1},j_{-1}} - \psi_{i,j-1} - 2\psi_{i^{ni+1},j} + 2\psi_{i,j}\right] = \frac{K_h}{d^4}\left[\psi_{i+2,j} + \psi_{i-2,j} + \psi_{i,j-2} + 2\left(\psi_{i-1,j+1} + \psi_{i+1,j-1} + \psi_{i-1,j+1} + \psi_{i,j}\right) - 8\left(\psi_{i+1,j} + \psi_{i-1,j} + \psi_{i,j+1} + \psi_{i,j-1}\right) + 2\psi_{i,j}\right] + \frac{1}{\rho H}\rho a\,|\,v\,10\,|\left(\frac{v_{i+1,j-}v_{i,j}}{\Delta x} + \frac{u_{i,j-1-}u_{i,j}}{\Delta y}\right) -$$

$$\frac{r}{Hd^2}\left[\psi_{i+1,j} + \psi_{i-1,j} + \psi_{i,j-1} + \psi_{i,j-1} - 2\psi\,\mathrm{i,j}\right] + \frac{1}{H^2}\left[\left(\frac{C_D\rho_a v_{10} u_{10}}{\rho} + \frac{r}{d}\left(\psi_{i+1,j} - \psi_{i,j}\right)\right)\frac{H_{i-1,j-}H_{i,j}}{\Delta x}\right] = 0 \tag{10}$$

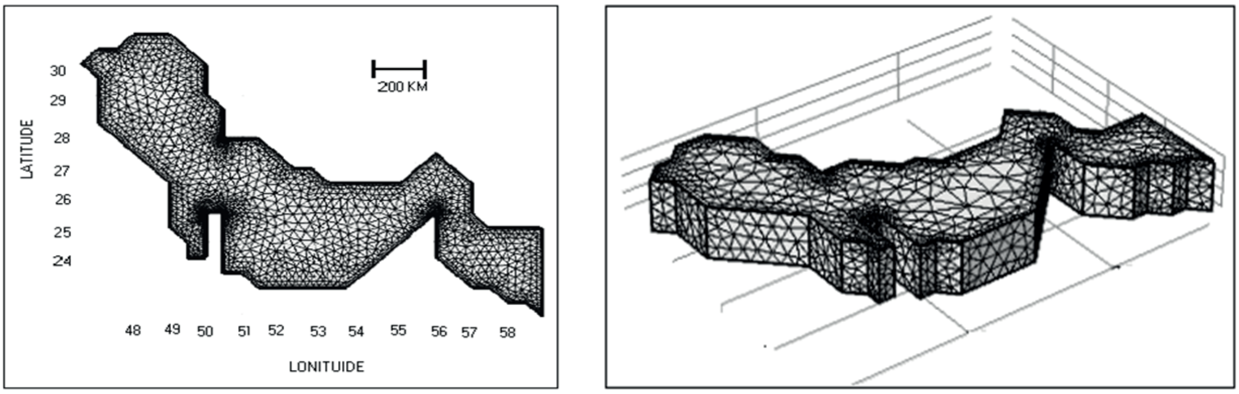

Figure 1. The 2D (left) and 3D (right) Persian Gulf network

Equation (10) is solved explicitly and all derivatives are approximated by the central difference method. The equation is written in terms of tension in the surface, middle and bottom of the water and the ψ function is calculated. The equations are specified for all points of the network. The Persian Gulf is divided into three layers, the first layer at the surface, the second layer in the depth of 10 meters below the surface, and the third layer at a depth of 40-m and the equations for each layer for all nodes have written and solved. FORTRAN's programming language has been used for computing, and ultimately velocity data is plotted by contra and surfer software (Bennett, 1977). To solve the equations, the method of the matrix coefficients is applied in the Mathematica software (Smith, 1986).

3. Results

The proposed model has a network with dimensions that covers the entire Persian Gulf, and the Gulf with a slightly hand-made change is a grid of non-regular triangular elements (Figure 1) and due to the importance of coastal areas has come out in some of the smaller grid areas.

From the results of the model shown in Figures 2 to 4, the flow in the Persian Gulf has a counterclockwise rotation in the middle. In winter, the speed of the prevailing northwest winds is the highest than in other seasons, and the surface flow through the Oman Sea and the Strait of Hormuz is accompanied by a return flow in the middle of Persian Gulf. As it is clear from the figures derived from the model results, at the depth of 40 meters, only one circulation cycle is seen, while several circulation cycles are visible in the surface and the depth of 10 meters.

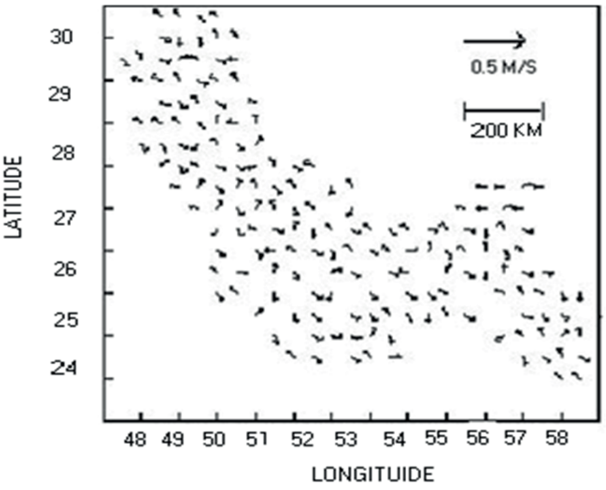

Figure 2. Water velocity at surface

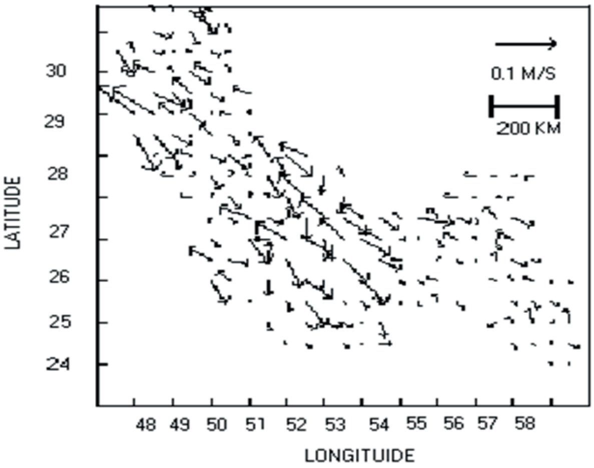

Figure 3. Water velocity in the depth of 10 meters from the surface

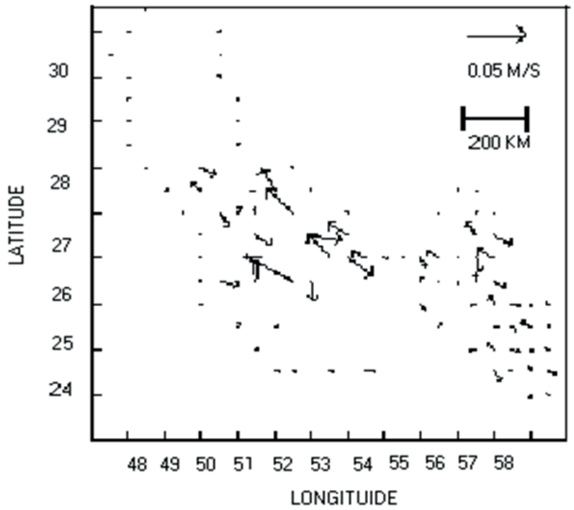

Figure 4. Water velocity in the depth of 40 meters from the surface

In summer, the speed of the northwest prevailing winds decreases, the inflow of the northern rivers in the Persian Gulf reduces, and the surface inflow from the Oman Sea to the north of the Persian Gulf is more progression. In the spring, the wind speeds from the northwest are relatively high, and they are relatively low in autumn. The rise of the Saudi-Emirate coastal currents in the figures can be due to continuous wind blowing in the northern half of the Persian Gulf to the south, which can create a down-current along the coast of Saudi Arabia and an upwelling along the coast of Iran. The existence of the Oman coastal flow can be attributed to strong winds along the coasts of Somalia, Yemen, and Oman. Extreme evaporation in the Persian Gulf is not compensated by rainfall at the surface that can be one of the reasons for the presence of ocean water flow from the Indian Ocean parallel to the coast of Iran with the counterclockwise direction in the Persian Gulf. Another important factor in this circulation is the wind drift caused water to be displaced on the surface. These two factors are the reason of entering the Oman Sea waters with lower salinity and density to the surface of Persian Gulf, and the Persian Gulf deep waters with the higher salinity and density depart from the Strait of Hormuz. The average current in the Persian Gulf is often a surface westward flow into the Gulf and along the coasts of Iran.

4. Discussion and Conclusion

A review of various models shows that in almost all valid models, the smooth stream entering the Persian Gulf travels along the Iran coasts and in the direction of counterclockwise, which is also seen in the model presented. This circulation is caused that the fresh water being transported to the Persian Gulf, and because of high evaporation in this area, the saline water dumps from the surface into the bottom, makes the vertical water movement, increasing of salinity, and decreasing of temperature in lower layers.

According to the studies by Monte-Michel ship, in six research round trips in the Persian Gulf, the most important points are summarized as follows: The northern winds are caused increasing the wave velocity towards the coastline of Iran in winter, and also enhancing the currents intensity in summer, which is also in agreement with the model presented.

The waters lost due to evaporation in the sea region are compensated by water entering from the Oman Sea, which is ultimately caused the water circulation through the Strait of Hormuz (Figure 4). In addition, the superiority of the existing model is that the velocity at various depths can also be calculated. In the model presented by Swift and Bower (2003), water circulation in the Persian Gulf is from the coast of Iran in the north of the Persian Gulf to the western end of the Persian Gulf near the mouth of Arvandrood and the coasts of Kuwait, which then returns from the southern coast of Qatar to Bahrain and again to the Strait of Hormuz.

In the model provided by Hunter, the model network consists of 331 homes along the horizon, each of which is divided into five levels, and the model was run as the steady state for internal speeds of about 23 days. The following results were obtained from this model:

Water entry and exit with low and high salinity from the Strait of Hormuz, the governing circulation due to the density in the center and south of Persian Gulf, and evaporation caused down-streams at the bottom.

According to both Hunter's schematic circulation model described earlier(Hunter, 1983), and that proposed by Reynolds (1993a), the flow is predominantly density driven with surface flow inward from the Strait of Hormuz and adjacent to the Iranian coast (ROPME, 1985). A southward coastal flow is present along with entire southern coast of the RSA. The flow stagnates east of Qatar, where high evaporation and sinking forms a dense, bottom flow to the northeast and out of the Strait of Hormuz (Reynolds, 1993b).

The presented model, in addition to the fact that all of the cases are visible in the figures, is more accurate because it contains a grid of non-regular triangular elements, and the term of time is also considered. Many results from the model cannot be described by Hunter's model. Water circulation, the vertical movement and horizontal currents generated by wind power, density, friction, water inlet of rivers, tides and bottom friction discussed and examined and the equations were solved with respect to all terms which represents the difference of the model in comparison with any other models run in the Persian Gulf.

Examining the existing terms concluded that the most prevailing forces in the Persian Gulf are evaporation and wind drift. Furthermore, the density changes resulting from evaporation have a significant contribution to the Persian Gulf water circulation, but the friction terms have no greatly affections on the movement of water masses in the Persian Gulf.

Always on the surface, there is a water flow from the Gulf of Oman to the Persian Gulf, with diverse direction of the flows in lower layers. The currents created on the surface of Persian Gulf generate a counterclockwise movement, and also at the head of Persian Gulf, a low-pressure current, and at the center of Persian Gulf, a high-pressure current.

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