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Evaluation of wind induced currents modeling along the Southern Caspian Sea

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ABSTRACT

To improve our understanding of the Caspian Sea hydrodynamics, its circulation is simulated with special focus on wind-driven currents of its southern basin. The hydrodynamic models are forced with a newly developed fine resolution wind field to increase the accuracy of current modeling. A 2D shallow water equation model and a 3D baroclinic model are applied separately to examine the performance of each model for specific applications in the Caspian Sea. The model results are validated against recent field measurements including AWAC and temperature observations in the southern continental shelf region. Results show that the 2D model is able to well predict the depth-averaged current speed in storm conditions in narrow area of southern coasts. This finding suggests physical oceanographers apply 2D modeling as a more affordable method for extreme current speed analysis at the continental shelf region. On the other hand the 3D model demonstrates a better performance in reproducing monthly mean circulation and hence is preferable for surface circulation of Caspian Sea. Monthly sea surface circulation fields of the southern basin reveal a dipole cyclonic-anticyclonic pattern, a dominant eastward current along the southern coasts which intensifies from May to November and a dominant southward current along the eastern coasts in all months except February when the flow is northward. Monthly mean wind fields exhibit two main patterns including a north-south pattern occurring at warm months and collision of two wind fronts especially in the cold months. This collision occurs on a narrow region at the southern continental shelf regions. Due to wind field complexities, it leads to a major source of uncertainty in predicting the wind-driven currents. However, this source of uncertainty is significantly alleviated by applying a fine resolution wind field.

1. Introduction

The Caspian Sea, a landlocked body of water between Asia and Europe, is an important economic region and exposed to extensive industrial use. As a source of global energy resource, the Caspian Sea is subject to increasing oil exploitation and therefore oil pollution. The increase of the exposure of the Sea to industrial use necessitates a more accurate understanding of its physical characteristics including its current features. Although previous research has focused on studying the circulation of the Caspian Sea, some issues in simulation of the current field still remain unresolved.

First, contrary to tide-induced currents, wind-driven current modeling involves uncertainties in wind patterns over the Sea. Since currents over the Caspian Sea are primarily wind-driven (Sarkisyan et al., 1976; Ghaffari et al., 2013), their accurate simulations depend to a great extent upon the wind data resolution (Kitazawa and Yang, 2012). However, to the best of our knowledge, previous studies have not applied well-resolved spatial changes of wind field over the Caspian Sea to predict its current field. For example, Ibrayev et al. (2010) used the ECMWF-ERA15 re-analysis atmospheric data with a grid spacing of 1.125° × 1.125° to simulate seasonal variability of the Caspian Sea circulation. Turuncoglu et al. (2013) developed a coupled atmosphere-ocean model to reproduce the Caspian climatology including its currents. The atmospheric model was applied with a resolution of 50 km. Gunduz and Özsoy (2014) used the seasonal mean ECMWF Re-Analysis (ERA-40) with a resolution of 1.125° as atmospheric forcing in simulating the Caspian Sea seasonal circulation. In this study, we aim at increasing the accuracy of current modeling by applying a 0.1° resolution 31-year wind field. Furthermore, we examine the monthly wind fields of the Caspian Sea to identify sources of uncertainty in wind patterns.

In addition to the lack of long-term high resolution wind data for the Caspian Sea, high resolution hydrodynamic model of the Southern

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Caspian Sea circulation is also absent in literature. To address this issue, an unstructured grid fine resolution model is developed to study the main oceanographic features of the Caspian Sea with focus on its southern region. The model also uses a hybrid sigma-z coordinate system to cooperate the advantages of both coordinate systems in simulating coastal and open ocean features (Kara et al., 2010).

Another gap in the Caspian Sea current simulation is the lack or scarcity of field measurements. Simulated current fields validated against observational data, especially in continental shelf regions are rare. To fill this gap, current measurements were conducted at stations located at the southern continental shelf regions. The currents were recorded by acoustic Doppler current profiler (AWAC) for a period of 14 months. In this research, these recent field data are used to calibrate and evaluate the developed numerical models.

In this paper, we simulate current field of the Caspian Sea by applying an unstructured triangular grid (used in both 2D and 3D hydrodynamic models), a hybrid sigma-z levels for vertical mesh (used in the 3D hydrodynamic model) and wind data with an accuracy of 0.1°. The purposes of the paper are to (1) investigate monthly surface circulation of the Caspian Sea; (2) evaluate capabilities of the 2D hydrodynamic model against the 3D hydrodynamic model for current field modeling of the Caspian Sea with the aid of measured data for a period of fourteen months and (3) study the wind field of the Southern Caspian Sea to identify sources of uncertainty in wind-driven currents.

2. Governing equations

In this paper, both 2D and 3D hydrodynamic models are applied.

2.1. The 2D hydrodynamic model

For 2D modeling of the Caspian Sea, the 2D hydrodynamic module of PMODynamics is applied in this paper. PMODynamics, Persian Model for Ocean Dynamics, is an Iranian numerical model developed for coastal engineering studies by some of the authors and some other hydrodynamic modelers in NAMROOD Consulting engineers. The Model is applicable in different fields of coastal engineering, including simulations of tidal currents, wind-driven currents and coriolis induced currents, currents in large scale environments (oceans), wave generated currents, large and small scale wave generation and wave propagation simulations, coastal morphology, sediment transportation and finally tidal analysis and tidal parameters extraction. Comprehensive information about PMODynamics software can be gained at http://pmodynamics.pmo.ir/en/home.

The 2DH hydrodynamic module solves the Shallow Water Equations (SWE) which can be written in the conservative form as follow:

$$\frac{\partial \eta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) - \Omega q + gh\frac{\partial \eta}{\partial x} - C_f u\sqrt{u^2 + v^2} - \frac{\rho_a}{\rho_w} C_d u_w \sqrt{u_w^2 + v_w^2} = -\frac{h}{\rho_w}\frac{\partial p_a}{\partial x} + \frac{\partial}{\partial x}\left(\nu_t \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_t \frac{\partial u}{\partial y}\right)$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + \Omega p + gh\frac{\partial \eta}{\partial y} - C_f v\sqrt{u^2 + v^2} - \frac{\rho_a}{\rho_w} C_d v_w \sqrt{u_w^2 + v_w^2} = -\frac{h}{\rho_w}\frac{\partial p_a}{\partial y} + \frac{\partial}{\partial x}\left(\nu_t \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_t \frac{\partial v}{\partial y}\right)$$

where t is the time, x and y are Cartesian coordinates, g is gravitational acceleration, η is water surface elevation, u and v are velocity components, h is water depth, $p = uh$ and $p = vh$ are flux components, u_w, $v_w =$ are wind velocity components, C_d is air-fluid drag coefficient, C_f is friction coefficient, p_a is air pressure, ν_t is eddy viscosity and Ω is Coriolis parameter.

This model solves the equation on mesh vertex layout. More details and verifications for this model were presented by Namin et al. (2004).

The second-order Roe scheme on an unstructured grid has been used to solve SWE.

2.2. The 3D hydrodynamic model

Among many available 3D or quasi-3D numerical models applicable for modeling current circulation in water bodies, we applied the MIKE3D-FM model (DHI, 2017). However, other popular models like FVCOM (The Finite Volume Coastal Ocean Model), TELEMAC3d, POM (The Princeton Ocean Model), HYCOM (The Hybrid Coordinate Ocean Model), or EFDC (The Environment Fluid Dynamics Code), which have their own numerical assumptions and methodology, would meet our purpose. One of the considerable advantages of the MIKE model is the existence of practical dynamic-link libraries for working with (generation and analysis of) input and output data. This superiority is one of our main motivations for selecting this model. These libraries have been used in this paper for either analyzing the outputs or producing the inputs.

In addition, the MIKE3D-FM model not only makes it possible to couple computational engines and data bases but also it consists of multiple computational tools, such as different kinds of wave and hydrodynamic modules as well as powerful graphical tools in the Windows platform. However, in the present work, the graphical and other computational tools (except for the MIKE3D-FM model) of this software package were not used.

Furthermore, the capability of the MIKE3D-FM model helps us generate a hybrid vertical mesh (the combination of z and sigma coordinates in vertical direction) in order to cooperate the advantages of both coordinate systems in simulating coastal and open ocean features and produce an efficient 3D computational grid.

In the 3D baroclinic model, the 3D incompressible Reynolds averaged Navier-Stockes equations are solved with Boussinesq's approximation and the hydrostatic pressure assumption in addition to transport equations for temperature and salinity. The governing equations are solved based on the second order finite volume scheme. Fluxes at interfaces of cells are determined using the Riemann solver (Roe, 1981; Namin et al., 2001, 2004; Badiei et al., 2008; Chegini and Namin, 2011). In this model, the Volga river discharge and atmospheric forcing including wind stress, short and long wave fluxes, evaporation and precipitation are considered.

The equations are the continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

and momentum equations in x and y direction respectively,

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial vu}{\partial y} + \frac{\partial wu}{\partial z} = \Omega v - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial x} - \frac{g}{\rho_0}\int_z^{\eta} \frac{\partial \rho}{\partial x} dz + F_u + \frac{\partial}{\partial z}\left(\nu_t \frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x} + \frac{\partial wv}{\partial z} = -\Omega u - gh\frac{\partial \eta}{\partial y} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial y} - \frac{g}{\rho_0}\int_z^{\eta} \frac{\partial \rho}{\partial y} dz + F_v + \frac{\partial}{\partial z}\left(\nu_t \frac{\partial u}{\partial z}\right)$$

where z is vertical coordinates, u, v and w are the velocity components in three dimensions, p_a is air pressure, F_v and F_u are the effects of horizontal stresses generated by eddy viscosity and ρ_0 is the reference density of water. Note that some parts of the mathematical model (such as radiation stresses) are not carried out, since they are not applied in this paper. In this formulation water density is depend only on temperature and salinity.