Numerical simulation of the long-term balance of salinity in the Gulf

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Abstract
The scarcity of freshwater resources in the area of the Gulf countries has led to increasing use of desalination plants to produce freshwater, which may give rise to higher salinity in the Gulf. Therefore, the prediction of the long-term balance of salinity in this semi-enclosed area is of great importance in terms of the environment. In this study, the salinity balance in the Gulf is modelled using MITgcm, the MIT General Circulation Model. The simulation is configured with realistic geography and bathymetry in spherical polar coordinates, and the implicit free surface form of the pressure equation is employed. Data on initial condition of salinity, desalination capacity and projections of wind, temperature, evaporation, and precipitation as well as river discharge are used as inputs for the model. This study simulated the long-term salinity balance in the Gulf from January 2005 to December 2060. The good agreement between the simulated results and observational data (WOA13 data) for the monthly-averaged salinity distribution for 2005-2012 verified the application of MITgcm for this problem. The prediction shows that the annually-averaged salinity in the Gulf is continually increasing.

1. INTRODUCTION

The Gulf (also called the “Persian Gulf” or “Arabian Gulf”) is a marginal sea partially enclosed by the continental landmasses of the Gulf countries and connected with the Indian Ocean. It has a surface area of 251,000 km²; the maximum length is about 990 km, while the minimum width is 56 m; the average depth is 36 m [Sadrinasab and Kämpf 2004]. The evaporation in the Gulf is very strong, at 1.44 m/year [Privett 1959], while precipitation and runoff are very weak, at 0.226 m/year [Dames and Moore, 1978] and 0.46 m/year [Masoud and Kaveh, 2011] respectively. What is worse is that due to the scarcity of freshwater resources in this area, a large number of desalination plants have been established to produce freshwater, a result of which the salinity in this area is very high. The increasing salinity has a serious adverse impact on the environment; therefore the prediction of the balance of salinity in this area is of great importance.
The MIT General Circulation Model (MITgcm) is a numerical model designed for the study of atmosphere, oceans and climate; it has non-hydrostatic capacities, which enable it to study a very wide range of phenomena, from the advection of flow on a small scale to a global scale [Adcroft et al. 2004].

The main objective of this study is to examine the long-term balance of salinity in the Gulf using a 3D numerical model. We simulate the salinity in the Gulf from January 2005 to February 2060 by utilizing the MIT General Circulation Model and compare the salinity between the observations and simulations (2005~2012). The present work will demonstrate that the salinity in the Gulf will increase continually if no mitigation measures are taken for the current situation. The result sections are organized as follows: the governing equations are presented in Section 2, the model setup is summarized in Section 3, the results are described in Section 4, and conclusions are drawn in Section 5.

2. GOVERNING EQUATIONS

The horizontal momentum equation, the vertical momentum equation and the continuity equation can be expressed, respectively, as (Adcroft et al., 2008):

\[
\frac{D\mathbf{v}_h}{Dt} + (2\mathbf{\Omega} \times \mathbf{v})_h + \nabla_h \Phi = F_{\mathbf{v}_h} \tag{2.1}
\]

\[
\frac{D\mathbf{v}_h}{Dt} + \mathbf{k} \cdot (2\mathbf{\Omega} \times \mathbf{v}) + \frac{\partial \Phi}{\partial r} = F_{\mathbf{v}_r} \tag{2.2}
\]

\[
\nabla_h \cdot \mathbf{v}_h + \frac{\partial \mathbf{v}_r}{\partial r} = 0 \tag{2.3}
\]

Where:

\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{\nu} \cdot \nabla \quad \text{is the total derivative}
\]

\[
\mathbf{\nu} = (u, v, \dot{r}) \quad \text{is the velocity}
\]

\[
\mathbf{\Omega} \quad \text{is the Earth's rotation}
\]

\[
\Phi \quad \text{is the geopotential}
\]

\[
\mathbf{k} \quad \text{is a unit vector in the vertical direction}
\]

and \( F_{\mathbf{v}_r} \) are forcing and dissipation of \( \mathbf{v} \)

The equation of state, equation for potential temperature and equation for salinity can be expressed as (Adcroft et al., 2008):

\[
b = b(\theta, S, r) \tag{2.4}
\]

\[
\frac{D\theta}{Dt} = F_{\theta} \tag{2.5}
\]

\[
\frac{DS}{Dt} = F_S \tag{2.6}
\]

Where:

\[
b \quad \text{is the buoyancy}
\]

\[
\theta \quad \text{is potential temperature}
\]
$S$ is the salinity

$F_{\theta}$ are forcing and dissipation of $\theta$

and $F_{S}$ are forcing and dissipation of $S$

As the vertical kinematic boundary condition, the vertical velocity is zero at the bottom; the following equation is used for expressing the horizontal kinematic boundary condition:

$$\vec{v} \cdot \vec{n} = 0$$  \hspace{1cm} (2.7)

where $\vec{n}$ is the normal to a solid boundary.

3. MODEL SETUP

In this study, the spherical polar coordinate (Figure 1) is used, which has two advantages: first, it is more accurate for such a large-scale problem in terms of the coordinates; and second, it is more useful when the Earth’s rotation is considered.

![Figure 1. The spherical polar coordinate](image)

The domain under study is 47.2875°-57.2875° in the zonal direction and 23.3875°-30.4125° in the meridional direction. There is no universally accepted criterion for the selection of grid resolution in a MITgcm simulation. The simulation was first run with a grid size of 0.01°×0.01°, and then coarser grid sizes were tested; finally, a resolution of 0.05°×0.05° is utilized, which produces almost the same results as in the case of 0.01°×0.01° and saves more than 10 times the computing time. Therefore, the setup in the present study is configured as a computational grid consisting of 200 grid cells in the zonal direction and 140 grid cells in the meridional direction. Ten layers are employed in the vertical direction, and the thicknesses (from surface to bottom) are: 5 m; 8.45 m; 14.27 m; 24.11 m; 40.73 m; 68.8 m; 116.23 m; 196.35 m; 331.71 m; 560.37 m. The reason for the selection of this kind of
configuration in the vertical direction is that the average depth of the Gulf is only 50 meters, which means that the shallow layers are more important.

The bathymetry data are drawn from the Scripps Institution of Oceanography, University of California San Diego [Becker 2009]; Matlab is employed to process the data (see Figure 2) and to write the data into a binary file.

The data on wind and temperature are obtained using downscaling methods, and the initial condition of salinity is obtained from a combination of three different studies [Allsop and Yao 2010; Yao and Johns 2010; Levitus et al 2013]. The study conducted by Privett [1959] is referenced for the evaporation; Dames and Moore’s study [1978] is used for the precipitation; the main river discharge into The Gulf is summarized by Masoud and Kaveh [2011]; Thoppil and Hogan [2010] studied the situation on heat flux; and the conclusions drawn by Reynolds [1993] are used for the tidal constituents.

![Figure 2: The bathymetry of The Gulf](image)

The desalination plants around the Gulf are summarized by Dawoud and Mulla [2012], and the desalination capacity in this area is shown in Figure 3.
Figure 3: Seawater desalination capacity in the Gulf

Figure 4: Comparison between simulated results and observational results
4. RESULTS AND DISCUSSION

It is difficult to get an accurate initial condition of salinity in the Gulf from one single study, so a combination of three different studies is used in the present work. Firstly, the salinity in January 2005 is produced by using the salinity in January 2007 [Allsop & Yao 2010] as an initial condition and simulating back to January 2005; the data on the surface salinity fields [Yao and Johns 2010] are utilized for the calibration of the simulation; and then the WOA 2013 data [Levitus et al 2013] on various points are used for the final calibration. The monthly averaged simulated results for 2005-2012 are compared to those from WOA 13 data [Levitus et al 2013].

The MITgcm-simulated results show that the model performs rather poorly in predicting the observed salinity in the eastern open boundary condition because of the complicated process in the mixing zone and the simplification employed for the setup of the open boundary condition. The model has a tendency to over-predict the salinity during fall and winter and underestimate the salinity during spring and summer. There are several reasons for these deviations; for example, some desalination plants were not working normally. Overall, the match between the simulated results and the observational data is quite good for such a large scale, and the comparisons for 4 locations in various latitudes (47.2875° - 57.2875°) are shown in Figure 4.

The long-term balance of salinity is simulated from January 2005 to December 2060. The salinity in this area is predicted to be increasing continually because the huge desalination operations in this area have already disrupted the balance, which introduces the situation that the total amount of desalination and evaporation is larger than that of precipitation and runoff, and the Indian Ocean cannot compensate the water budget adequately; therefore, mitigation measures have to be taken.

The speed of the increase in salinity is also increasing because of the decreasing freshwater in this area, the increasing temperature and so on.

Generally, the salinity along the south coast will be higher than that along the north coast; one possible reason for this scenario is that there are more desalination plants along the south coast, and another possible factor is the circulation pattern.

![Figure 5. Salinity in the Gulf in 2014](image-url)
The salinity near the shoreline is higher than that in the far field, and the main reason for this is that almost all the desalination plants are located near the shore; also, the shallow bathymetry in the near field as well as the circulation pattern could be other factors accounting for this.

The results for the simulated salinity in 2014, 2037 and 2060 are shown in Figures 5 to 7.

5. CONCLUSIONS

Numerical simulation of the long-term balance of salinity in the Gulf has been conducted using the MIT General Circulation Model. The comparison between the data and simulated results for the salinity from 2005 to 2012 demonstrates that MITgcm can produce satisfactory results for salinity distribution in a semi-enclosed sea. The simulated results show the following conclusions:

(1) Without mitigation measures, the salinity in the Gulf will increase continually.
(2) The speed of the increase of salinity in the Gulf will increase as well.
(3) The salinity along the south coast will be higher than that along the north coast.
(4) The salinity near the shoreline will be higher than that in the far field.

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