A Study of the Performances of Different Turbulence Schemes in Numerical Simulation of Hydrodynamics of a Semi-Closed Sea (Persian Gulf)


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A Study of the Performances of Different Turbulence Schemes in Numerical Simulation of Hydrodynamics of a Semi-Closed Sea (Persian Gulf)

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ABSTRACT
Complex process of turbulent mixing in Persian Gulf that is a semi-closed sea makes it a good media to test the performance of different turbulence schemes. In this research, we used the 3D ocean model COHERENS (COupled Hydrodynamical Ecological model for REgioNal Shelf seas) for the Persian Gulf with the open boundary in the Hormuz Strait. Of the turbulence schemes for the vertical diffusion available in the COHERENS, we tested four models to investigate the hydrodynamic characteristics of the Persian Gulf. The results show that all of the schemes presented the sea surface salinity (SSS) distribution rather accurately but the k-l and flow-dependent models results have better agreements with observations. The most noticeable difference between the results of four schemes is the differences found in the simulation of turbulent parameters. The turbulent closure schemes generally provide better results, but the algebraic schemes show turbulent parameters far from reality and they do not show substantial changes with time. Generally, the vertical structures of turbulence in the water basins and parameterization of turbulence in water column is very sensitive to the selection of the type of the turbulence scheme. However, large-scale structures that take place within the inflow and outflow area are approximately quasi-horizontal, and the vertical small-scale turbulence does not affect them as much. As a result, they show less sensitivity to the performance of various turbulence schemes.

Introduction
The state of turbulence due to instabilities of fluid flows is ubiquitous in nature and engineering. In the fluid environments like the ocean and atmosphere, the growth of instabilities causes turbulence flows as three-dimensional small scales and two-dimensional large scales. Turbulence in geophysical flows occurs usually at different scale mainly at small, meso, and...
large scales. The small-scale turbulence in the ocean is mainly responsible for the vertical diffusion, while the so-called large-scale two-dimensional turbulence is mainly responsible for the horizontal mixing (Bidokhti 2004). Since turbulence plays an important role in the ecosystem processes in the oceans, choosing suitable turbulence models in numerical modeling in each region may improve results in various fields such as hydrodynamics, biological, pollution, and sedimentation (Tuomi 2011). Calculation or prediction of such flows and identifying the hydrodynamic of the area by taking into account the turbulence is important in every respect, for example in terms of spread of contaminations and environmental dispersion, fisheries, shipping, and even security problems. In the past few decades, several numerical ocean models to study the hydrodynamics of the ocean have been developed. These numerical models include different turbulence schemes, like algebraic turbulence schemes and turbulence closure schemes. The turbulence schemes implemented in numerical programs have been developed and tested to represent one or more of the following physical processes: 1) turbulence generated by tidal friction in the bottom layer, 2) wind-induced turbulence in the surface layer, 3) enhancement of the bottom stress due to the interaction of waves and currents at the sea bottom, 4) diurnal and seasonal cycles of heating and cooling, including the evolution of thermocline, 5) shear-induced mixing at river fronts (Luyten et al. 1999) and river plumes are the major source of nutrients, sediments, and other pollutants into the coastal waters (Nekouee et al. 2015).

Ocean circulation is critically dependent on the way turbulent mixing occur and hence better schemes in parameterizations of turbulence is essential in ocean modeling. Several works have documented the model results of turbulence mixing parameterization and have compared the performance of their applications. Obino (2002) in a modeling study compared the performances of two turbulence closures in estimating the kinetic energy of the Bohai Sea and also he found that a higher turbulent kinetic energy (TKE) is produced using the $k-l$ scheme compared to the $k-e$ scheme. Tuomi et al. (2011) in a study of performance of vertical turbulence models in the modeling of hydrodynamics of the Baltic Sea found that the $k-l$ and $k-e$ models showed slightly better agreement with the measurements than the algebraic schemes. Luyten et al. (1996) presented a family of turbulence closure models for stratified shallow water flows with application to the Rhine outflow region. Kutay Celebioglu et al. (2005) compared results of various turbulence closure models to be used in a hydrodynamic 3D code in the Delaware Bay. They found that the low-order models such as constant viscosity approach and mixing length theory do not produce satisfactory results for salt transport. This suggests that the use of more complex approaches than low-order closures are needed to better characterize the nature of turbulent flows in nature. Cheng Liu et al. (2010) used several schemes for modeling turbulence tide and salinity stratification in an estuary. The results show that the two-order scheme produces larger stratification and density gradients. The other schemes overpredict the maximum salinity. Mehmet Ilıçak et al. (2008) studied the performance of two-equation turbulence closures in three-dimensional simulations of the Red Sea overflow. They found that all two-equation turbulence models are able to capture the vertical structure of the overflow and eddy diffusivities are too small in KPP (K profile parameterization) and too large in Mellor–Yamada scheme. KPP and Mellor–Yamada schemes produce the largest deviations from the observations. Hamidi et al. (2015) also compared the Mellor and Yamada scheme in Princeton Ocean Model for Lake Michigan and showed the overprediction of diffusivity in comparison with observation. The other five closures fall in between, showing similar deviations.
Here we study the hydrodynamics of a semi-enclosed basin namely the Persian Gulf, a shallow tidal sea, which is a turbulent dominated environment. The complexity of the vertical mixing processes makes the Persian Gulf a good candidate for testing different turbulence models. The oceanic region, comprised of the Persian Gulf, Strait of Hormuz, and Gulf of Oman, is the most important waterways in the world. The important role of Persian Gulf regarding world oil trade, economy, and a source of rich source of food including 150 different species of fish makes it very important to understand the physical characteristics of this Gulf. Some studies that have been conducted in Persian Gulf are as follows. Yao and Johns (2010) studied water mass formation and circulation in the Persian Gulf and water exchange with the Indian Ocean using observations and HYCOM model. They demonstrated the role of wind forcing on the inflow into the Persian Gulf. According to the study of Swift and Bower (2003) in the Persian Gulf, the densest water forms in winter in the northern end of the Gulf rather than along the warmer southern and western coasts. With the exception of small amounts of water directly above the seafloor, most water flowing out of the Gulf mixes across a density front that separates the Gulf Deep Water within the Gulf from the Indian Ocean inflow surface water. Mosaddad et al. (2012) studied the thermocline development in the Persian Gulf using observations and numerical modeling.

However, there is a lack of reliable knowledge about what works, why, and in what ways, and there is no study carried out to investigate which turbulence schemes are suitable for the simulation of hydrodynamic of the Persian Gulf; a question that is going to be answered in this research. The main idea of the research is to study the performance of several turbulence schemes in a 3D hydrodynamic model to predict the fields of physical parameters, including turbulent diffusivity in the Persian Gulf.

**Materials and methods**

The COHERENS (COupled Hydrodynamical Ecological model for REgioNal Shelf seas) three-dimensional model, which has been specifically made for the study of the hydrodynamics of shallow seas, is used. This model also includes various turbulence schemes, which could be tested in the Persian Gulf as a semi-enclosed basin. The length of the Gulf is about 1000 km in NW_SE direction, and the width varies from a maximum of 338 km to a minimum of 56 km in the Strait of Hormuz, and the surface area is approximately $3.39 \times 10^5$ km$^2$ (Yao and Johns 2010). The Persian Gulf climate conditions are dry, subtropical, and known as the hottest world water region. The average depth of the Persian Gulf is 35 m, with a maximum depth of 110 m in the Strait of Hormuz (Yao and Johns 2010). For these reasons, the whole Persian Gulf constitutes a continental shelf; therefore, COHERENS is a suitable model for the study of this semi-enclosed sea.

**Description of the model**

COHERENS is a three-dimensional hydrodynamic multipurpose model for coastal and shelf seas, which is coupled to biological, sediment, and contaminant models, and resolves mesoscale (wind, tides, inertial oscillations) and seasonal scale (thermocline formation, plankton blooms) processes. The program has been developed over the period of 1990–1998 by a multinational European group (Luyten et al. 1999). The model equations are formulated either in Cartesian coordinates ($x_1, x_2, x_3$) or in spherical coordinates ($\lambda, \varphi, x_3$), where the $x_3$-axis is
directed upwards along the vertical. The Cartesian system uses the f-plane approximation (uniform Coriolis frequency). The hydrodynamic part of the model uses the following basic equations: the momentum equations with the Boussinesq approximation and the assumption of vertical hydrostatic equilibrium, the continuity equation, and the equations of temperature and salinity (Luyten et al. 1999).

An important advantage of the model is its transparency due to its flexibility because of the possibility of selecting different types of forcing for a particular application (Luyten et al. 1999). Hamidi et al. (2013) in their study “Evidence of Multiple Physical Drivers on the Circulation and Thermal Regime in the Green Bay of Lake Michigan” worked on physical processes (drivers or forcings) of hydrodynamic model for Green Bay, which is an elongated bay with similar geometry to Persian Gulf. According to their work, currents and temperatures in the Great Lakes exhibit a wide range of time and spatial scales, in response to atmospheric forcing, Earth’s rotation, and geometry. Because of the interaction of drivers, water exchange between Green Bay and Lake Michigan has effects on water quality that are at least as important as those of watershed discharges. In shallow environments like the Persian Gulf, the main drivers are wind, density, bathymetry, evaporation, and advection.

**Vertical mixing parameterization**

One of the most intricate problems in oceanographic modeling is an adequate parameterization of vertical exchange processes or vertical mixing. In the present model they are represented through the eddy viscosity ($\nu_T$) and eddy diffusivity ($\lambda_T$) coefficients. Values for these two parameters are to be provided by a turbulence scheme. The choice of an appropriate turbulence model not only affects the physical but also the biological, sediment, and contaminant parts of the program. The selection of a suitable scheme is often a difficult task since it depends on the type of physical processes specific for the simulated water basin (e.g., tide, thermocline, river, and fronts), the vertical resolution of the model, and the amount of CPU time. For this reason a broad range of turbulence schemes are incorporated, ranking from simple algebraic formulations up to 2.5 order closure schemes with additional transport equations for turbulence quantities (Luyten et al. 1999). The simpler algebraic formulations use empirical relations for turbulent parameterization. Closure schemes use turbulent kinetic energy equation, which is as follows (All symbols are presented in Appendix A):

$$\frac{\partial k}{\partial t} + \frac{\partial (vk)}{\partial x_1} + \frac{\partial (vk)}{\partial x_2} + \frac{\partial (\omega k)}{\partial x_3} - \frac{\partial}{\partial x_1} \left( \lambda_T \frac{\partial k}{\partial x_2} \right) - \frac{\partial}{\partial x_3} \left( \left( \frac{\nu_T}{\sigma_k} + \nu_b \right) \frac{\partial k}{\partial x_3} \right) = \nu_T M^2 - \lambda_T N^2 - \varepsilon \quad (1)$$

where $k$ is the turbulence kinetic energy and $N^2$ and $M^2$ are the squared buoyancy and shear frequencies, respectively, and $\varepsilon$ denotes the dissipation rate of turbulence kinetic energy. Here we present briefly the turbulence parameterizations that are commonly used in this model.

**Pacanowski and Philander parameterization (PP)**

The formulation of Pacanowski and Philander (1981) is an algebraic and Richardson number dependent formulation. Values for eddy coefficients $\nu_T$ and $\lambda_T$ are provided as a function
of Richardson number by

\[ \nu_T = \nu_p f_p^{np} (Ri) + \nu_b \]  

(2)

\[ \nu_T = \nu_T f_p (Ri) + \nu_b \]  

(3)

\[ f_p (Ri) = (1 + \alpha_p Ri)^{-1} \]  

(4)

The Richardson number (a measure of stability of water column) is defined as the ratio of the squared buoyancy frequency to the squared vertical shear:

\[ Ri = N^2 / M^2 \]  

(5)

where

\[ N^2 = \frac{g}{J} \left( \beta_T \frac{\partial T}{\partial x_3} - \beta_s \frac{\partial s}{\partial x_3} \right) \]  

(6)

\[ M^2 = \frac{1}{J^2} \left( \left( \frac{\partial u}{\partial x_3} \right)^2 + \left( \frac{\partial v}{\partial x_3} \right)^2 \right) \]  

(7)

and \( \beta_T, \beta_s \) are the thermal and salinity expansion coefficients and \( J \) is grid points along the vertical transect. To prevent turbulence becoming too large in the case of unstable stratification (\( Ri < 0 \)), the following constraining condition for \( f_p \) is imposed

\[ \frac{\nu_T}{\nu_p} \approx f_p^{np} < \nu_{max} \]  

(8)

\[ \frac{\lambda_T}{\nu_T} \approx f_p^{np+1} < \frac{1}{\nu_{max}} \]  

(9)

The scheme has been primarily developed for application in global ocean models. It has the advantage of being less sensitive to vertical resolution than the more advanced turbulence closures. In the absence of stratification, the coefficients take uniform values, which make the scheme less reliable for the study of neutral tidal and wind-driven flows (Pacanowski et al. 1981). According to the study by Hamidi et al. (2015) on the recent advances in improvement of modeling effort for shallow regions in stratified condition, critical improvements in developing realistic simulations of stratification in the bay have been obtained. These are via consideration of water clarity conditions that affect heat adsorption and varying default parameters, particularly in the vertical diffusivity, in the Lake Michigan model framework.

**Flow-dependent parameterization**

In shelf and coastal seas, tides are a prominent source of turbulence. Observations in the Irish Sea indicate that the eddy viscosity is proportional to the magnitude of the tidal current...
A suitable parameterization for tidal flow can then be written as

\[ \nu_T = (\alpha(x_1, x_2, t)\phi(\sigma) + v_{\omega})f_m(Ri) + \nu_b \]  
(10)

\[ \lambda_T = (\alpha(x_1, x_2, t)\phi(\sigma) + v_{\omega})g_m(Ri) + \lambda_b \]  
(11)

The flow field is represented by the depth-independent factor \( \alpha \) given by

\[ \alpha = K_2\left( \nabla^2 + \nabla'^2 \right) / (H^2\omega_1) \]  
(12)

The damping functions \( f_m(Ri) \) and \( g_m(Ri) \) take the form given by the Munk–Anderson scheme (Luyten et al., 1999). Following Glorioso and Davies (1995) the wind-induced turbulence is related to the surface friction velocity using the simple form

\[ v_{\omega} = \lambda_s u_{es} \]  
(13)

where \( \lambda_s \) is a constant tunable parameter and the surface friction velocity \( u_{es} \) is given by

\[ p.u_{es} = \tau_{b}^{\frac{1}{4}} = \left( \tau_{b1}^{2} + \tau_{b2}^{2} \right)^{\frac{1}{2}} \]  
(14)

and \( \omega_1 \) is a characteristic frequency (Luyten et al. 1999).

**Mellor and Yamada parameterization**

One of the more popular closure schemes is that of Mellor and Yamada (1982). This closure scheme includes prognostic equations from which the turbulent kinetic energy \( (k) \) and mixing length scale \( (l) \) are derived (Mellor et al. 1982). The 2.5 order of turbulence closure scheme of Mellor and Yamada with the modifications introduced by Galperin et al. (1988) is used in this model. The eddy coefficients are expressed as

\[ \nu_T = S_m k^{1/2} l + \nu_b \]  
(15)

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

where \( S_m \) and \( S_h \) are usually referred as the stability functions

\[ S_m = \frac{0.556 + 2.18G_h}{1 + 20.4G_h + 53.1G_h^2} \quad S_h = \frac{0.699}{1 + 17.3G_h} \]  
(16)

where

\[ G_h = \frac{\tau^2}{k N^2} \]  
(17)

and \( \nu_b, \lambda_b \) are prescribed background viscosity and diffusivity coefficients. It is interesting to note that the stability functions have no explicit dependence on the current shear as in the original Mellor–Yamada formulation. As shown by Luyten and Deleersnijder (1996), this improves the stability of the scheme.
The dissipation rate is parameterized according to
\[ \varepsilon = \varepsilon_0 k^{3/2} / l \] (18)

Parameterizations for the mixing length obtained with Blackadar (1962) formulation that is
\[ \frac{1}{l} = \frac{1}{l_1} + \frac{1}{l_2} + \frac{1}{l_\alpha} \] (19)

**k-\varepsilon parameterization**

In the two-equation turbulence closure model, k-\varepsilon derived from Luyten et al. (1996) is used.

The turbulent kinetic energy (k) and dissipation rate (\varepsilon) are determined with the transport equation (1). The eddy coefficients are expressed as
\[ v_T = S_u k^2 / \varepsilon + v_b \]
\[ \lambda_T = S_b k^2 / \varepsilon + \lambda_b \] (20)

where \varepsilon is taken as the second turbulence variable instead of \( l \). \( s_u \) and \( s_b \) are given by
\[ S_u = \frac{0.108 + 0.0229 \alpha_N}{1 + 0.471 \alpha_N + 0.0275 \alpha_N^2} \]
\[ S_b = \frac{0.177}{1 + 0.403 \alpha_N} \] (21)

where
\[ \alpha_N = \frac{k^2}{\varepsilon^2} N^2 \] (22)

In addition, here parameterizations for the mixing length are obtained according to (1).

**1. Model setup**

Cartesian coordinate system is used for horizontal directions; we tested both four-minute and two-minute resolutions and results show two-minute resolution is more appropriate for this kind of study of hydrodynamic of the Persian Gulf with \( \Delta x = 3200 \) m (east–west direction) and \( \Delta y = 3704 \) m (north–south direction). For the vertical coordinate, we used sigma coordinate system. Complex coastline and topographies of the bottom are the most difficult cases for modeling of shallow seas. Better hydrodynamic simulation of these basins is possible using an orthogonal coordinate system that also includes the topography, which is called sigma coordinate system. Then the following coordinate transformation is applied.
\[ (\tilde{t}, \tilde{x}_1, \tilde{x}_2, \tilde{x}_3) = (t, x_1, x_2, Lf(\sigma)) \] (23)
where

\[
\sigma = \frac{x_3 + h}{\zeta + h} = \frac{x_3 + h}{H}
\]  \hspace{1cm} (24)

is the commonly used \(\sigma\)-coordinate varying between 0 at the bottom and 1 at the surface (Luyten et al. 1999). To choose the proper resolution for the vertical direction, the model was tested with different number of sigma layers including 4 different resolutions (5 layers, 10 layers, 15 layers, and 20 layers), and results show that 10 layers is appropriate for the numerical modeling of Persian Gulf basin, regarding its bottom topography and chosen horizontal resolution. Persian Gulf coastline and its bathymetry are based on ETOPO-2 data, which are obtained from the digital data of seabed and bulge of the earth with latitudinal and longitudinal geographical two-minute networks (Figure 1).

The model is forced by climatologic monthly mean atmospheric forcing (wind speed, air temperature, humidity, cloud cover, and precipitation) at 10-m reference height above ground derived from 54 years (1948–2002) of National Oceanic and Atmospheric Administration (NOAA) data. Meteorological forcing is set to be non-uniform in space and time over the model grid points. The advection scheme that is used for momentum and scalars is either total variation diminishing (TVD) scheme, which uses the super bee limiter as a weighting function between the upwind scheme and the Lax–Wendroff scheme in the horizontal or the central scheme in the vertical. The density and the coefficients \(\beta_x\) and \(\beta_T\) are evaluated using the general equation of state. The bottom stress is evaluated using the quadratic friction law. The uniform bottom friction coefficient was chosen at 0.005 \((\text{m/s})\) and uniform value for the bottom roughness length that was chosen as 0.015 \((\text{m})\), based on the bottom roughness of the basin. The wave-current interaction module is also activated. Wave height \(h_s\) and period \(t_w\) are uniform in space and time, as the mean typical values of the area. The Geernaert et al. (1986) formulation for the neutral surface drag coefficient \(C_D\) is selected, that is often the condition over most of the ocean.

![Figure 1. Bathymetry of the study area and locations of stations 1, 2, and 3 and transects A and B.](Image)
Model has an eastern open-ocean boundary in the Strait of Hormuz. Amplitudes and phases of the four major tidal constituents including M₂, S₂, O₁, and K₁ are prescribed as constant values along the boundary (Table 1). Uniform initial temperature and salinity fields with values of 20°C and 38 psu are also used, which is reasonably close to mean observational evidence (Alessi et al. 1999). Time steps of 20 s and 30 s were chosen for the 2D (Barotropic) and 3D (Baroclinic) modes, respectively.

Table 1. Tidal amplitudes and phases prescribed at the eastern boundary.

<table>
<thead>
<tr>
<th>Tidal constituent</th>
<th>Period (h)</th>
<th>Amplitude (m)</th>
<th>Phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal lunar semidiurnal M₂</td>
<td>12.42</td>
<td>1.1</td>
<td>214.980</td>
</tr>
<tr>
<td>Principal lunar diurnal O₁</td>
<td>25.82</td>
<td>0.6326</td>
<td>192.200</td>
</tr>
<tr>
<td>Principal solar semidiurnal S₂</td>
<td>12.00</td>
<td>0.4416</td>
<td>248.900</td>
</tr>
<tr>
<td>Lunisolar diurnal K₁</td>
<td>23.93</td>
<td>0.3378</td>
<td>289.300</td>
</tr>
</tbody>
</table>

Model setup with different turbulence models

From the vertical turbulence models available in the COHERENS, we utilized four turbulence schemes to investigate the hydrodynamic of Persian Gulf. This includes two turbulence closure schemes: k-ε, and Mellor and Yamada (k-l) with the modifications introduced by Galperin et al. (1988) and two algebraic formulations by Pacanowski and Philander (PP) and flow-dependent parameterization. For the k-ε and k-l models, we used one-equation model for transport equation, the “Blackadar” formulation for mixing length, and limiting conditions for turbulence variables are enabled. The stability functions are expressed in terms of the Richardson number.

Results and discussion

The model is initialized in winter when vertical stratification is weak throughout the Gulf (Mosaddad et al. 2012). Simulation time of the experiments, in a fully prognostic mode, is 10 years, which is sufficiently long for a steady-state seasonal cycle of circulation and water mass properties to develop in the Persian Gulf. Figure 2 shows the distribution of sea surface salinity in summer in Persian Gulf using four turbulence models. Fresh water of the Gulf of Oman enters the Persian Gulf and this low salt intrusion reaches up to the north west of the Persian Gulf. Comparison between the results with different turbulence schemes shows that all of the schemes predicted the salinity distributions reasonably well, but the PP and k-ε model underestimated the surface salinity compared to the observations (Reynolds 1993). According to Reynolds’ field studies, the salinity of the Persian Gulf is variable from 36 psu to 39 psu in different places of the Gulf in the summer. The k-l and flow-dependent schemes results have good agreement with observations and they simulated lengthier fresh water intrusions compared to those simulated by other schemes.

Figure 3 shows intrusion of fresh water to northwestern part of the Persian Gulf in the summer. The k-l and flow-dependent schemes simulated lengthier fresh water intrusions into the Gulf compared to other schemes but the flow-dependent scheme shows it as more diffusive than the k-l scheme. Because the k-l closure scheme uses prognostic equation in their formulation for simulation, it can have the results with more resolved fields.
At the center of the Persian Gulf the instability occurs that is probably of a baroclinic nature as it is produced by the intrusion of fresher water into the basin (Figure 4 with higher resolution only part of the Persian Gulf, the central part is shown). The meso-scale eddies

Figure 2. Surface salinity distribution in the Persian Gulf. (a) flow-dependent, (b) PP, (c) $k-l$, (d) $k$.n.
due to this instability are clearly observed. The $k-l$ and flow-dependent schemes simulate this instability more realistically and the $k-l$ scheme shows it as more diffusive pattern. This is probably related to the role of vertical and horizontal diffusion parameterization in $k-l$. The

**Figure 3.** Intrusion of fresh water in the northwestern part of Persian Gulf and flow patterns (a) flow-dependent, (b) PP, (c) $k-l$, and (d) $k-e$. 
Figure 4. Generation of quasi-horizontal meso-scale structures due to instability and flow pattern for different turbulence schemes for the central part of the Persian Gulf. (a) flow-dependent, (b) PP, (c) $k-l$, and (d) $k-e$. 
performances of other schemes to simulate this phenomenon are weaker. Regarding these results, the flow-dependent scheme is more competent in the simulation of these meso-scale eddies. This is because of the more realistic formulation of this scheme. The homogeneous form of the eddy viscosity parameterization (Eq. 10) has been used in recent years for the prediction of tidal currents and surface elevations in the Northwest European Continental Shelf (e.g. Davies 1990; Davies et al. 1997), in the Irish and Celtic Seas (e.g. Davies and Jones 1992; Davies 1993), and the shelf edge off the West coast of Scotland (Proctor and Davies 1996). According to the results of the study by Davies (1993), this parameterization of eddy viscosity proved sufficient to be able to reproduce the essential features of the observed vertical profiles of only non-stratified tidal currents (as only for the inside of the Persian Gulf water in winter, see below).

Figure 5 shows temperature profiles in the station 3 (Figure 1) in winter and summer and it is very clear that the thermocline is formed in summer. However, in winter there is uniformity in temperature profile from the surface to bottom inside the Persian Gulf. Comparison between the turbulence scheme performances with observation (Mosaddad et al. 2012) shows that all of the models presented the vertical structure of temperature in winter and summer rather well. However, there are some differences between simulations of the four schemes. For both winter and summer, the flow-dependent scheme overestimates the temperature and the k-l scheme has a better agreement with the observations than the other schemes.

![Figure 5](image_url)

**Figure 5.** Predicted and observed temperature profiles (°C) in the station 3 at (a) winter and (b) summer.
Figure 6 shows the vertical temperature distribution along transect A (Kuwait-Iran, Figure 1). All schemes show the formation of thermocline rather well, but the PP scheme shows that the intensity of thermocline formed is weaker compared to those predicted by the other schemes.

**Figure 6.** Temperature distribution along transect A (Kuwait-Iran) for four turbulence schemes: (a) flow-dependent, (b) PP, (c) k-l, (d) k-ε.
Figure 7. Vertical temperature distribution along transect B (United Arab Emirates-Iran, Figure 1) (a) flow-dependent, (b) PP, (c) k-l, (d) k-ε.
the others. The flow-dependent scheme shows higher surface temperature than those of other predictions, while the turbulent closure schemes show similar results and are closer to the observation (Bidokhti et al. 2009).

Figure 8. Turbulent parameters, (a) turbulent kinetic energy (TKE), (b) TKE dissipation rate, (c) turbulent viscosity, and (d) turbulent diffusivity.
Figure 7 shows the vertical temperature distribution along transect B (United Arab Emirates-Iran, Figure 1). The PP scheme shows that the intensity of thermocline formed is weaker compared to those predicted by others. The flow-dependent scheme shows higher surface temperature than those of other predictions. On the right side of the figures, the signs of the baroclinic instability are evident as shown in Figure 3. It is also evident on thermocline

Figure 9. Time series of change in TKE, dissipation rate, and mixing length for the four turbulence schemes.
structure. Because of the mixing in the water column, surface temperature is also lowered. Results of the turbulence closure schemes show that the turbulence created by this instability is larger. In addition, $k-l$ scheme has simulated a larger turbulence kinetic energy compared to $k-e$ scheme and has caused more diffused thermocline adhesion compared to that of other schemes by creating more mixing in the water column. Signs of the wavy thermocline in the area have also been observed as it is shown in the observations by others (e.g. Swift and Bower 2003, Msadad et al. 2012).

Figure 8 presents the turbulent parameters profiles at the station 2 including TKE, dissipation rate of turbulent kinetic energy, eddy viscosity $\nu_t$, and eddy diffusivity $\lambda_t$ in the winter. In the comparison of turbulent parameters, the differences between the turbulence models are large. Comparison with global range of this parameter shows that the turbulent closure schemes generally provide better results, but the algebraic schemes underestimate these parameters. The mean global range of TKE, dissipation rate, eddy viscosity $\nu_t$, and eddy diffusivity $\lambda_t$ are $10^{-4}$ J/kg (Obino et al. 2002), $10^{-6}$ m$^2$/s$^3$ (Almeida de Souza et al. 2013), $10^{-2}$ m$^2$/s (Wijesekera et al. 2003), and $10^{-2}$ m$^2$/s (Ilıçak et al. 2008), respectively. In addition, the $k-l$ scheme presents closer results to those of the global range than the $k-e$, and it shows the changes with depth as well. As this basin is mainly tidal driven (and to some extent wind) it is expected to have higher values of diffusivities particularly in winter as the water column stability is weaker, and lower values in summer as the thermocline is well developed (Figure 9).

The largest values of TKE and dissipation rate are found in the surface layer. Estimation of coefficients of vertical eddy viscosity and eddy diffusivity with flow-dependent scheme was considerably different compared to those of the global rates.

Figure 9 shows the time series of change in TKE, dissipation rate, and mixing length for the four turbulence schemes in station 2 (Figure 1) in the winter. The results indicate that algebraic schemes, unlike closure scheme, do not show changes with time and indicate constant value with time, which is unrealistic. This is related to the calculation technique of eddy coefficients as the closure schemes obtained eddy coefficients by solving a transport equation, but the algebraic schemes obtained eddy coefficients by using empirical relations. Between the closure schemes, the $k-l$ scheme for TKE and dissipation rate presents better results than the $k-e$. The $k-l$ scheme shows an increasing trend from January 1 to January 30 and shows a decreasing trend from February 1 to March 30, which are closely related to the intensity of forcing during these periods. For both closure schemes, the strong TKE occur in January, as strong cold northerly winds over the Persian Gulf in this month is common. Hence, results are in agreement with our expectations. Table 2 displays a comparison between the results of different schemes of maximum TKE at each station, for the surface and at the bottom that are similar in magnitudes to the values reported by Obino et al. (2002). They studied the effect of

<table>
<thead>
<tr>
<th>Table 2. Maximum TKE at the surface and at the bottom for four turbulence schemes. Values are expressed in $10^{-3}$ J/kg.</th>
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<tbody>
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<td>Scheme</td>
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two turbulence closure schemes to simulate TKE in Bohai Sea that is similar to the Persian Gulf. They found that the range of TKE at surface and bottom is about 0.3 and 0.16, respectively, in $10^{-3}$ J/kg.

**Figure 10.** Evolution of thermocline for four turbulence schemes: (a) flow-dependent, (b) PP, (c) $k-l$, and (d) $k-e$. 
Figure 10 showed the evolution of thermocline in station 1 from May 21 to August 18 for four turbulent schemes. All schemes are able to simulate the evolution of thermocline. However, there are some differences. The PP scheme simulates deeper thermocline with weaker

Figure 11. Evolution of dissipation rate of TKE for four turbulence schemes: (a) flow-dependent, (b) PP, (c) k-l, and (d) k-ε.

Figure 10 showed the evolution of thermocline in station 1 from May 21 to August 18 for four turbulent schemes. All schemes are able to simulate the evolution of thermocline. However, there are some differences. The PP scheme simulates deeper thermocline with weaker
intensity. The $k-l$ and $k-e$ schemes show similar results. The flow-dependent scheme shows the best result as compared with observations (Figure 5).

Figure 11 shows the evolution of dissipation rate of turbulent kinetic energy in station 1 for four turbulent schemes. Figure 11 a, b shows algebraic schemes that unlike closure schemes do not show changes of dissipation rate of turbulent kinetic energy with time and present constant values for this parameter with time that is unrealistic but changing with depth. We know that in an area where the thermocline is formed, the density is increased downwards and $\frac{\partial \rho}{\partial z} < 0$; in this case, the turbulence should work against buoyancy forces. Therefore, the buoyancy forces cause turbulence dissipation in addition to molecular friction (Bidokhti 2004). Figure 11c illustrates this fact well. This means that only the $k-l$ closure scheme is able to simulate the evolution of dissipation of TKE more appropriately, as the mean stratification of the water column in this basin evolves with time.

**Conclusions**

A 3D hydrodynamic ocean model, namely COHERENS, was implemented in the Persian Gulf with an open boundary in the Hormuz Strait, to test the performances of four turbulence schemes. The study focuses on finding points of difference between four vertical mixing parameterizations applied to the simulation of hydrodynamic of the Persian Gulf. The different results among the models, for the same scenarios, are a consequence of the fact that each model gives a different relative importance to the different physical processes involved in the turbulent closure scheme, that is, shear, buoyancy, and dissipation. The model results were compared with the measured data set. The comparison of the performance of four turbulence schemes shows that there are several differences in the results:

All of the schemes presented the sea surface salinity distribution rather well in summer and fresh water intrusion to northern part of Gulf, and the PP and $k-e$ model underestimated the surface salinity compared to that of observations. The $k-l$ and flow-dependent models have better agreements with observations and they simulated longer fresher water intrusion into the Persian Gulf compared to that of the other schemes.

The surface flow velocity distributions predicted by the four turbulence schemes are similar, but the current speed simulated with turbulent closure schemes is greater compared to those of the algebraic schemes.

The $k-l$ and flow-dependent schemes simulated the larger scale instability (probably baroclinic) in the center of Gulf and the $k-l$ scheme predicted a more diffused structure due to this instability. This is related to the role of vertical and horizontal diffusion parameterization in $k-l$, as this scheme uses prognostic equations of turbulence, as opposed to algebraic ones.

Comparison of winter and summer temperature profiles with observations shows that all schemes suggest the formation of thermocline correctly, but the $k-l$ scheme results have a better agreement with observations for both winter and summer, and the PP scheme shows that the intensity of thermocline was weaker than that by the others.

Most noticeable difference between four schemes is found in the simulation of turbulent parameters. The turbulent closure schemes generally provide better results, but the algebraic schemes show amounts of turbulent parameters far different from that of expected. This is related to the performance of such schemes. Between the closure schemes, the $k-l$ scheme represented better results than the $k-e$, because the $k-e$ is a first and half order closure scheme but the $k-l$ is a 2.5-order turbulence closure scheme.
The results of time series of turbulent kinetic energy, dissipation rate, and mixing length for the four turbulence schemes show that algebraic schemes do not show changes with time and indicate constant values for these parameters as expected. This is related to the calculation technique of eddy coefficients as the closure schemes obtained eddy coefficients by solving transport equations, but the algebraic schemes obtained eddy coefficients by using empirical relations. Between the closure schemes, the $k-l$ scheme has better results.

Generally, the study of vertical structures in water basins and parameterization of turbulence in water column is very sensitive to the selection of the type of the turbulence scheme. However, large-scale structures that take place within two inflow and outflow are approximately quasi-horizontal; therefore, vertical turbulence does not affect them as much. As a result, they show less sensitivity to the performance of various turbulence schemes.

The comparison between the model results and field measurements of the rate of dissipation of turbulent kinetic energy shows that all models require modification through the implementation of internal wave parameterization, in order to predict the observed levels of turbulence kinetic energy and dissipation more accurately.

According to the results of our study, for the study of the performances of different turbulence schemes in numerical simulation of hydrodynamics of Persian Gulf, it seems that the $k-l$ and $k-\varepsilon$ turbulence closure schemes have a high priority compared to algebraic schemes to estimate turbulent parameters, particularly for the investigation of time variations. Although the $k-l$ scheme that is a 2.5-order scheme which is more competent than the $k-\varepsilon$ scheme. In addition, no sensible changes are seen between turbulence closure schemes in the simulation of quasi-horizontal large-scale structures. However, the flow-dependent algebraic scheme has a good performance in these large-scale structures and in the simulation of large-scale hydrodynamic instabilities. In a basin as the Persian Gulf, as the flow has a more modulated turbulent structure it may be more appropriate to even use hybrid turbulence scheme as the Reynolds averaged schemes-large eddy simulation (e.g., Peng and Haase 2008) that can be for future research in marine environments.

References


Appendix A

Nomenclatures

t \quad \text{Time (s)}

u, v \quad \text{Horizontal velocity components (m s}^{-1}\text{)}

T \quad \text{Temperature(}^\circ\text{C)}

S \quad \text{Salinity(psu)}

F \quad \text{Coriolis frequency}

x, y, z \quad \text{Cartesian coordinates}

Ri \quad \text{Richardson number}

i \quad \text{Mixing length(m)}

G \quad \text{Acceleration of gravity}

P \quad \text{Pressure}

\text{c}_p \quad \text{Specific heat of seawater at constant pressure}

I \quad \text{Solar irradiance}

H \quad \text{Water depth}

Greek letters

\Sigma \quad \text{Sigma coordinate}

\rho \quad \text{Density (kg m}^{-3}\text{)}

\rho_0 \quad \text{Reference density}

\varepsilon \quad \text{Energy dissipation rate (m}^2\text{s}^{-3}\text{)}

\nu_T \quad \text{Eddy viscosity coefficient (m}^2\text{s)}

\lambda_T \quad \text{Eddy diffusivity coefficient(m}^2\text{)}

\beta_i \quad \text{Thermal expansion coefficient}

\beta_s \quad \text{Salinity expansion coefficient}

\lambda_s \quad \text{Constant tunable parameter}

\zeta \quad \text{Water elevation}

u_{ss} \quad \text{Surface friction velocity(m/s)}

\omega_1 \quad \text{Characteristic frequency}

\tau_{11}, \tau_{21} \quad \text{Horizontal components of the stress tensor}

\lambda_H \quad \text{Horizontal diffusion coefficient for salinity and temperature}

Acronyms

TKE \quad \text{Turbulence kinetic energy}