Estimation of turbulence parameters in a shallow sea using numerical simulation with sensitivity to vertical mixing parameterization

M. Mohandesi Namin1*, A. A. Bidokhti2 & A. Karami Khaniki3

1 Graduate School of Marine Science and Technology, Science and Research Branch, Islamic Azad University, Tehran, Iran
2 Institute of Geophysics, University of Tehran, Tehran, Iran
3 Soil Conservation and Watershed Management Research Institute, Tehran, Iran

*E-mail: Mohandesi_n@yahoo.com

Received 07 May 2015; revised 31 October 2016

Persian Gulf coastline and its depth are obtained based on ETOPO-2 data that has been interpolated and slightly smoothed onto a two-minute resolution. Cartesian coordinate system is used for horizontal and sigma coordinate with 10 layers is used for the vertical. From the turbulence schemes for the vertical diffusion available in the COHERENS, we tested four models to investigate the hydrodynamic characteristics of the Persian Gulf. These include two turbulence closure schemes: k-ε(one and half order), Mellor and Yamada (k-l, two and half order) and two algebraic schemes: Pacanowski and Philander (PP) formulation and flow-dependent parameterization. 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 turbulent parameters far from reality and they do not show substantial changes with time.

[Keywords: Turbulence scheme, Hydrodynamic numerical simulation, COHERENS Model, Persian Gulf]

Introduction

The state of the fluid, which is unstable continuously, is called turbulence. In fluids like the ocean and atmosphere, the growth of instabilities causes turbulence flows. The 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 diffusion1. 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 sedimentation2. In the past few decades, tremendous insight about the physics of turbulence is obtained by theoretical and experimental studies, geophysical observations, improved experimental methods and numerical modeling. These numerical models include different turbulence schemes, like algebraic turbulence schemes and turbulence closures. The turbulence schemes implemented in numerical programs have been developed and tested to represent one or more of physical processes. For example: 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 fronts3. Global thermocline circulation is critically dependent on the way turbulent mixing occur and hence better schemes in parameterizations of turbulence is essential in ocean modeling.

Several reports have documented the model results of turbulence mixing parameterization and have compared the performance of their applications. Obino4 in a study about simulation of the Bohai Sea circulation and thermohaline structure used COHERENS model and compared the results of the performances of two turbulence closures in estimating the kinetic energy of the basin and he found that a higher TKE is produced using the k-l scheme compared to the k-ε scheme. Tuomi et al5 in a study of performance of vertical turbulence models in the modeling of hydrodynamics of, the Baltic Sea, using the model COHERENS with the k-ε
model, k-l model and algebraic formulations by Munk and Anderson and Pacanowski and Philander (PP). The k-l and k-ε models showed slightly better agreement with the measurements than the algebraic schemes. Luyten et al., presented a family of turbulence closure models for stratified shallow water flows with application to the Rhine outflow region. They dealt with vertical one-dimensional modes of the stratification processes. KutayCelebiogluet, compared results of various turbulence closure models to be used in a hydrodynamic 3D code in the Delaware Bay. More specifically, six different turbulence closures, i.e. a constant eddy viscosity, an algebraic model, and 4 two-equation closure models were used for comparison. All of the models simulated the water surface elevations with reasonable accuracy, some more closely (k-α, k-kl) others a little less accurate (k-ε). 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 characterize the nature of turbulence better. Cheng Liu etal. used several schemes for modeling turbulence tide and salinity stratification in an estuary. The results show that the k-l scheme produces larger stratification and density gradients. Mellor and Yamada scheme over-predicts the amplitude of stratification signal. The other schemes over-predict the maximum salinity. Mehmet Ilicak et all studied the performance of two-equation turbulence closures in a 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- Yamadascheme.KPP, and Mellor and Yamada produce the largest deviations from the observations and the modified k-ε exhibits the smallest deviations. The other five closures fall in between, showing similar deviations.

Several studies have been conducted in this area as follows. Hosseinibalametal, studied three-dimensional numerical modeling of thermohaline and wind-driven circulations in the Persian Gulf. Hassanzadeh etal. studied numerical modeling of salinity variations due to wind and thermohaline forcing in the Persian Gulf. Fengchao Yao, studied water mass formation and circulation in the Persian Gulf and water exchange with the Indian Ocean. Mosaddad, et al, studied an observational and numerical modeling of thermocline development in the Persian Gulf. In none of them the role of different turbulence schemes were examined.

Here we study the hydrodynamics of a semi-enclosed basin namely the Persian Gulf, a shallow tidal sea that is a turbulent dominated environment. Since shallow waters are strongly influenced by the wind, tide, advection, and buoyancy, therefore turbulence is frequently expected in such an 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, are the most important water ways in the world. The important role of Persian Gulf regarding world oil trade, economy and a source of rich foods including 150 different species of fish makes it very important to understand the physical characteristics of these seas. However, the use of different turbulence schemes in simulation of the hydrodynamics of this region is required to test their performance in simulation of the hydrodynamics of this region. In this research, we studied 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 three-dimensional model, which has been specifically made for the study of the hydrodynamics of shallow seas, is used here. This model also includes various turbulence schemes. The study area for this research is the Persian Gulf that is a semi-enclosed basin. The length of the Gulf is about 1000 km in NW_SE direction, 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 $3.39 \times 10^5 km^2$. The Persian Gulf weather condition is dry, subtropical, and known as the hottest world water region. The average depth of the Persian Gulf is 35 m and a maximum depth of 110 m in the Strait of Hormuz. For these reasons, the whole Persian Gulf constitutes of a continental shelf; therefore, COHERENS is a suitable model for the study of this semi-enclosed sea. One of the main sources of data including temperature, density and salinity measurements for this semi-enclosed sea that were used in this study, is Mt. Mitchell
Cruise, which was carried out in summer and winter 1992 during 100 days from Feb. to Jul.\textsuperscript{20}

COHERENS is a three-dimensional hydrodynamic multi-purpose model for coastal and shelf seas, which is coupled to biological, re-suspension and contaminant models, and resolves meso-scale to seasonal scale processes. The model has been developed over the period of 1990–1998 by a multinational European group\textsuperscript{3}.

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 \(x_1\)-axis is directed upwards along the vertical, \(x_2\) is towards east and \(x_3\) is towards north. 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\textsuperscript{3}.

In Cartesian coordinates, these equations are:

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

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

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

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. The following coordinate transformation is applied.

\[
(\tilde{\xi}_1, \tilde{\xi}_2, \tilde{\xi}_3) = (x_1 x_2, Lf(\sigma)) \ldots (7)
\]

\[
\sigma = \frac{x_3 + h}{\xi + h} \ldots (8)
\]

is the commonly used \(\sigma\)-coordinate varying between 0 at the bottom and 1 at the surface\textsuperscript{1}.

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 \((\nu_v)\) and eddy diffusivity \((\lambda_v)\) 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 second and half -order closure schemes with additional transport equations for turbulence quantities\textsuperscript{3}. The simpler algebraic formulations use empirical relations for turbulent parameterization. Closure schemes use turbulent kinetic energy equation, which is as follows:

\[
\frac{\partial \xi}{\partial t} \frac{[\xi]}{[\xi]} - \frac{\partial \xi}{\partial x_1} \frac{[\xi]}{[\xi]} - \frac{\partial \xi}{\partial x_2} \frac{[\xi]}{[\xi]} - \frac{\partial \xi}{\partial x_3} \frac{[\xi]}{[\xi]} - \frac{\partial \xi}{\partial x_3} \frac{[\xi]}{[\xi]} = \nu_v \frac{[\xi]}{[\xi]} - \lambda_v \frac{[\xi]}{[\xi]} - \epsilon \ldots (9)
\]

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

\[
\nu_T = \nu_f f_T^w (Ri) + \nu_p \quad \ldots (10)
\]

\[
\lambda_T = \nu_f f_T^w (Ri) + \lambda_p \quad \ldots (11)
\]

\[
f_T (Ri) = (1 + a_T Ri)^{-1} \quad \ldots (12)
\]

The Richardson number is defined as the ratio of the squared buoyancy frequency to the squared vertical shear:

\[
RI = N^2 / M^2 \quad \ldots (13)
\]

where:

\[
N^2 = \frac{\beta}{T} \left[ \frac{\partial T}{\partial z} - \beta \frac{\partial \omega}{\partial z} \right] \quad (14)
\]

\[
M^2 = \frac{1}{T} \left( \frac{\partial \omega}{\partial z} + \frac{\partial \tau}{\partial z} \right) \quad (15)
\]

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

\[

\nu_T / \nu_p = f_p \nu_T < \nu_{\text{max}} \quad \ldots (16)
\]

\[

\lambda_T / \nu_T = f_p \nu_T < \nu_{\text{max}} \quad \ldots (17)
\]

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.

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) + \nu_p) f_p (Ri) = \nu_T \ldots (18)
\]

\[

\lambda_T = (\alpha (x_1, x_2, t) \phi (\sigma) + \nu_p) g_p (Ri) + \lambda_p \ldots (19)
\]

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

\[

\alpha = k (| U^1 v^1 |) / (| H^1 v^1 |) \quad \ldots (20)
\]

The damping functions \( f_m (Ri) \) and \( g_m (Ri) \) take the form given by the Munk-Anderson scheme. Following Glorioso and Davies\(^3\) wind-induced turbulence is related to the surface friction velocity using the simple form

\[

\nu_{\alpha} = \lambda \mu_{sx} \quad (21)
\]

Where \( \lambda \) is a constant tunable parameter and the surface friction velocity \( \mu_{sx} \) is given by

\[

\mu_{sx} = \frac{1}{3} \left( \sigma^1_{\mu} + \sigma^2_{\mu} + \sigma^3_{\mu} \right) \quad \ldots (22)
\]

And \( \omega_1 \) is a characteristic frequency [3].

**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. The 2.5 order turbulence closure scheme of Mellor and Yamada with the modifications introduced by Galperin et al.\(^1\) is used in this model. The eddy coefficients are expressed as

\[

\nu_T = S_a k^{1/2} l + \nu_p \quad \ldots (23)
\]

\[

\lambda_T = S_p k^{1/2} l + \lambda_p \quad \ldots (24)
\]

Where \( S_m, S_h \) are usually referred as the stability functions

\[

S_a = \frac{0.556 + 2.18 G}{1 + 20.4 G} + \frac{0.556 + 2.18 G}{1 + 17.3 G} \quad \ldots (25)
\]

Where

\[

G_h = \frac{k}{l} N^2 \quad \ldots (26)
\]

and \( \nu_p, \lambda_p \) 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 Deleersnijder and Luyten\textsuperscript{15}, this improves the stability of the scheme.

The dissipation rate is parameterized according to
\[
\varepsilon = \varepsilon_0 k^{3/2} / l \quad \ldots(26)
\]

Parameterizations for the mixing length obtained with Blackadar\textsuperscript{16} formulation, which is:
\[
\frac{1}{l} = \frac{1}{l_u} + \frac{1}{l_v} + \frac{1}{l_w} \quad \ldots(27)
\]

Two-equation turbulence closure model, k-\(\varepsilon\) derived in Luyten et al\textsuperscript{15} is used. The turbulent kinetic energy (\(k\)) and dissipation rate (\(\varepsilon\)) are determined with the transport equation (9). The eddy coefficients are expressed as
\[
\nu_e = S_k k^2 / \varepsilon + \nu_s \\
\lambda_e = S_k k^2 / \varepsilon + \lambda_s \\
\nu_e = S_k k^2 / \varepsilon + \nu_s \\
\lambda_e = S_k k^2 / \varepsilon + \lambda_s \quad \ldots(28)
\]

where \(\varepsilon\) is taken as the second turbulence variable instead of \(l_s\) and \(s_b\) are given by:
\[
S_k = 0.108 + 0.0229 z + 0.471 0.0275 z \quad S_k = 0.177 \quad \ldots(29)
\]

where
\[
\alpha_s = \frac{k}{\varepsilon} N^2 \quad \ldots(30)
\]

And here parameterizations for the mixing length are also obtained according to (9).

The Cartesian grid spacing of \(\Delta x=3200\)m (east-west direction) and \(\Delta y=3704\)m (north-south direction) for horizontal and sigma coordinate with 10 layers are used for vertical direction. 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 (fig1).

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 NOAA data. Meteorological forcing is set to be uniform in space but non-uniform in time. 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 \(\beta_s\) 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 (m/s) and uniform value for the bottom roughness length that was chosen as 0.015 (m). The wave-current interaction module is activated. Wave height \(h_w\) and period \(t_w\) are uniform in space and time. The Geernaert et al\textsuperscript{17} formulation for the neutral surface drag coefficient \(C_D\) is selected, that is often the condition over most of the ocean.

Model has an eastern open-ocean boundary in the Strait of Hormuz. Amplitudes and phases of the four major tidal constituents including \(M_2, S_2, O_1,\) and \(K_1\) are prescribed as constant values along the boundary. Uniform temperature and salinity fields with values of 20\(^\circ\)C and 38 psu are used, which is reasonably close to observational evidence\textsuperscript{18}. Time steps of 20 s and 30 s were chosen for the 2D (Barotropic) and 3D (Baroclinic) modes, respectively.

From the vertical turbulence models available in the COHERENS, we utilized four
turbulence models 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. 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, and 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.

Cartesian coordinate system is used for horizontal directions; we tested both four-minute and two-minute resolutions and results show two-minute resolution is appropriate for the study of turbulent parameters. To choose the proper resolution for the vertical direction, the model was tested with a different number of sigma layers including 4 different resolutions (5 layers, 10 layers, 15 layers, 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.

Results

The model is initialized in winter when vertical stratification is weak throughout the Gulf (e.g. Mosaddadet al.). Total 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.

Figures 2 to 5 presents the turbulent parameters profiles at the station one including turbulent kinetic energy (TKE), dissipation rate of turbulent kinetic energy, eddy viscosity $\nu_t$ and eddy diffusivity $\lambda_t$. In the comparison of turbulent parameters, the differences between the turbulence schemes are large as expected. Comparison with global range of this parameter shows that the turbulent closure schemes generally provide better results, but the algebraic schemes underestimate these parameters. In addition, the k-l scheme presents closer results to that of global range than the k-ε, and it shows the changes with depth as well. 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. The results show that all models require modification through the inclusion of an internal wave parameterization in order to be able to predict the observed levels of turbulent dissipation more correctly. Internal wave breaking is a typically unresolved mechanism, which contribute significantly to the vertical redistribution of momentum and scalars. The rate energy of dissipation of turbulent kinetic energy depends on the energy flux through the spectrum of the internal waves and depends on its parameters. Predictions of the energy contributed by the internal wave field to turbulence and ultimately lost to dissipation in the course of mixing the fluid were reviewed by Gregg (1989).
Fig 5. Profiles of diffusivity with four turbulent schemes, at the station 1

Fig 6 to 8 shows the time series of change in TKE, dissipation rate and mixing length for the four turbulence schemes. The results indicate that algebraic schemes, unlike closure scheme, do not show changes with time and indicate constant value for this parameter with time that 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-ε. 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. Hence, results are in agreement with our expectations.

Fig 9 shows monthly mean sea surface temperature of the Persian Gulf from the 10th year of modeling results for winter. The model results compared with the measured data and are consistent with Reynolds’ observation (fig 5-e), the surface temperature in winter in the Gulf shows a gradient from the northern part of the Gulf towards the Strait, increasing from about 15°C to 22°C. The performance of almost all the turbulence schemes produced surface temperature distributions reasonably well, except for the flow-dependent scheme, which overestimated the surface temperature. The use of different turbulence schemes in modeling temperature patterns shows the secondary role of horizontal temperature in this short-term exchange current. The large-scale structures that take place within two inflow and outflow are approximately quasi horizontal; therefore, vertical turbulence does not affect them as much. Again, this outflow is a meso to large scale with a rather low Rossby number and is less affected by the type of the turbulence schemes used.

Fig 10 shows temperature profiles in the station 2 (fig 1) in winter and summer and it is very clear that the thermocline is formed in summer. However, in winter because of existence of strong turbulence there is uniformity in temperature profile from the surface to bottom inside the Persian Gulf. Comparison between the turbulence schemes performances with observation (Reynolds’ (1993) summer survey)
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 winter, the flow-dependent scheme overestimates the temperature but the k-l scheme has a better agreement with the observations than the other schemes.

Fig 9. Monthly mean SST from the 10th year model output for winter. (a) flow-dependent, (b) PP, (c) k-l, (d) k-\(\varepsilon\), (e) surface temperature for winter, Mt. Mitchell Expedition

Fig 10. Predicted and observed temperature profiles (°C) in the station 2 (a) winter, (b) summer.

Fig 11 shows the vertical temperature distribution along transect A (Kuwait-Iran, fig 1). All schemes show the formation of thermocline rather well. Thermocline depth of about 15 meters is estimated. In the comparison of the performance of turbulent scheme, the PP scheme shows that the intensity of thermocline formed is weaker compared to those predicted by the others. The flow-dependent scheme shows higher surface temperature than those of other predictions with strong intensity. It seems that the k-l and k-\(\varepsilon\) turbulent closure schemes have better results than the others do.

Fig 12 showed the evolution of thermocline in x=200, y=600 for four turbulent schemes. All schemes are able to simulate the evolution of thermocline. Approximately the formation of thermocline starts from day 30 of simulation. However, there are some differences. The PP scheme simulates the more depth of thermocline with weak intensity. The k-l and k-\(\varepsilon\) schemes show similar results. The flow dependent scheme shows the best result.

Fig 13 showed the evolution of mixing length in x=200, y=600 for four turbulent schemes. Fig 13 a, b shows algebraic schemes that unlike closure
schemes do not show changes of mixing length with time and present constant value for this parameter with time that is unrealistic but changing with depth. Comparison between the performances of the turbulence closure schemes fig13c, d shows that the k-l closure scheme presents better result than the k-ε closure scheme. When the thermocline is formed, the k-l scheme shows decrease of mixing length well (compare fig13c with fig12). However, the k-ε closure scheme presents a higher value of mixing length in the first days.

Fig 11. Temperature distribution along transect A (Kuwait-Iran) for four turbulence schemes: (a) flow, (b) PP, (c) k-l, (d) k-ε

Fig 12. Evolution of thermocline for four turbulence schemes: (a) flow, (b) PP, (c) k-l, (d) k-ε

Fig 13. Evolution of mixing length for four turbulence schemes: (a) flow, (b) PP, (c) k-l, (d) k-ε

Fig 14 showed the evolution of dissipation rate of turbulent kinetic energy in x=200, y=600 for four turbulent schemes. Fig 14 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 value for this parameter with time that is unrealistic but changing with depth. We know that in an area where the thermocline is formed density is increased to upwards $\frac{\partial \rho}{\partial z} < 0$, in this case the turbulence should work against buoyancy forces. Therefore, the buoyancy forces cause turbulence dissipation in addition to molecular friction. Fig 14c well illustrates this fact. This means that only the k-l closure scheme is able to simulate the evolution of dissipation of TKE.
Discussion

- COHERENS, a 3D hydrodynamic ocean model, was implemented in the Persian Gulf with an open boundary in the Hormuz Straits. The study focuses on finding points of difference between four vertical mixing parameterizations applied to the estimation of turbulence parameters of the Persian Gulf. The comparison of the performance of four turbulence schemes shows that there are several differences in the results:
  - Noticeable difference between four schemes is found in the estimation of turbulent parameters. The turbulent closure schemes generally provide good results, but the algebraic schemes show amounts of turbulent parameters far different from that expected. This is related to the performance of such schemes. Between the closure schemes, the k-l scheme represented better results than the k-\(\varepsilon\) scheme, because the k-\(\varepsilon\) is a first and half order closure scheme, but the k-l is a 2.5 order turbulence closure scheme.
  - The investigation about time series of turbulent kinetic energy, dissipation rate and mixing length for the four turbulence schemes shows 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 a transport equation, but the algebraic schemes obtained eddy coefficients by using empirical relations.
  - The comparison between the results and field measurements of the rate of dissipation of turbulent kinetic energy shows that all models require modification through the initiation of an internal wave parameterization in order that they are able to predict the observed levels of turbulence dissipation more accurately.

- Comparison of winter and summer temperature profiles with observations shows that all schemes suggest the formation of thermocline correctly, but the PP scheme shows that the intensity of thermocline was weaker. For winter, the flow-dependent scheme overestimates the temperature but the k-l scheme has a better agreement with the observations than the other schemes.
- Simulation of SST for winter and comparison with observations shows that flow-dependent scheme overestimated the surface temperature.
- All schemes act well in the simulation of thermocline and forecasting the time evolution of them. However, the algebraic schemes are unable to forecast the turbulent parameters during thermocline formation.
- Overall, 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 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.

Conclusion

Differences between four schemes are found in the estimation of turbulent parameters. The comparison between the model results and field measurements show the turbulent closure schemes generally provide good results, but the algebraic schemes show amounts of turbulent parameters far different from reality.
Acknowledgement

Authors are so thankful to the anonymous reviewers and the editors of the journal for valuable suggestions that helped us to improve the quality of the manuscript.

References