Numerical Modeling of Turbulent Processes in outflow of the Persian Gulf

Akbarinasab, A.

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Abstract

In this study, measured hydrophysical data collected by the University of Miami researchers from the southern part of the Strait of Hormuz during the period December 1996 to March 1998 and climate data from the Qeshm island meteorological station were used to simulate water column turbulence south of the Qeshm Island, via General Ocean Turbulence Model (GOTM). The model does not use slip and fluxes as a bottom boundary condition. Therefore, the model's vertical domain was chosen so that the bottom does not influence the upper boundary layer simulation. The vertical domain considered for simulation is from \( z = 0 \) m, at the surface, to \( z = -110 \) m, in an equally spaced Cartesian grid of 1 meter. The time laps were three hours. The simulation results showed different seasonal turbulent kinetic energy (TKE) and thus, different penetration depths. In the cold season, TKE extends from the surface to bottom, but is restricted to the upper depths of thermocline layer. In addition, results show that the TKE is similar to the buoyancy frequency (N).

Keywords: Turbulent kinetic energy, Model GOTM, Strait of Hormuz, Buoyancy frequency

1. Introduction

Since, most real flows such as atmospheric boundary layer around the earth, oceanic flows, movement of clouds, river flows, blood circulation are turbulent, turbulence is most commonly studied in fluid mechanics, and yet, is one of the biggest unsolved problems of classical physics. It plays the basic role in engineering and geophysics (Falkovich & Sreenivasan, 2006). Internal hydrodynamic microstructures of marine waters including, field changes of temperature, salinity, and density in the vertical and horizontal directions. For example, the Persian Gulf outflow (PGO) is as a result of excessive evaporation of about 1.5 to 2 m/yr (e.g. Privett, 1959; Reynolds, 1992; Bower et al., 2000) saline water. These structures are the result of what causes mixing and turbulence in stratified oceans and seas. In the Persian Gulf, tides, breaking waves due to seabed topography, wind-driven currents and convection of the upper part of the water column are turbulence agents. Due to the stable stratification, two-layered conditions are mostly governed in the Persian Gulf. Also, internal waves which break in the middle layers of the sea can cause turbulence (Monin & Ozmidov, 1985). These Microstructures can affect sound communications and marine pollution on the marine environment. In this article, we modelled TKE penetration depth in different seasons for the Strait of Hormuz and analyzed how the buoyancy
frequency changed throughout seasons.

One of the usual turbulence models is \( k - \varepsilon \), though, not working properly under very adverse pressure gradients as the static pressure increases in the direction of the flow. \( k - \varepsilon \) is a second-order turbulent closure model. It contains two extra advection equations to calculate current turbulence characteristics. It can be used to calculate transport and diffusivity effects of turbulence energy. The first transport variable is the turbulence kinetic energy \( (k) \) and the second one is dissipation rate \( (\varepsilon) \). In other words, \( k \) determines the turbulence energy and \( \varepsilon \), the turbulence scale. Launder and Sharma (year missing) also used standard \( k - \varepsilon \) model in their investigations. The main objective of \( k - \varepsilon \) model can be the mixing-length model improvement, in such a way, that it can express an algebraic description for mixing-length in complex currents. \( k - \varepsilon \) model is efficient and accurate using for internal and external currents with a small pressure gradient. Its accuracy also decreases for flows with the adverse pressure gradient. In this research, we use \( k - \varepsilon \) turbulent closure equation in second-order closure method. This model is formed of shear or mechanical production \( (p) \), buoyancy production \( (B) \), vertical transport \( (T) \), turbulent kinetic energy viscosity dissipation \( (\varepsilon) \) parameters that are discussed as the followings:

\[
\partial_t K = p + B + T - \varepsilon \tag{1}
\]

In equation 1, shear or mechanical production \( (P) \) is proportional to shear frequency \( (S) \) and turbulent viscosity \( (V_t^m) \).

\[
p = V_t^m S^2 \tag{2}
\]

Buoyancy production \( (B) \) is proportional to buoyancy frequency and \( (N) \) and turbulent buoyancy diffusion \( (V_t^m) \)

\[
T = V_t^m \sigma_k^{-1} (\partial_z K) \tag{3}
\]

Turbulent kinetic energy viscosity dissipation rate is a combination of turbulent kinetic energy rate \( (\partial_t K) \) and semi empirical parameters \( c_{e1}, c_{e2}, c_{e3} \) and vertical transport term \( (\varepsilon) \)

\[
\partial_t \varepsilon = \frac{\varepsilon}{k} (c_{e1} P + c_{e3} P + c_{e2} \varepsilon) \tag{4}
\]

That input empirical parameters in this simulation are given from Burchard studies coefficients (Burchard et al., 1999).

2. Material and Methods

For the present model one-hundred layers and 2 minutes, time laps were considered. In this model, based on the selection of the number of layers and time intervals, a stable coefficient was determined to solving the equations avoiding instability. For detailed information about GOTM model validity, one could refer to the sixth chapter of Burchard’s book (Burchard, 2002). This type of model has been tested and used in many studies of the upper ocean mixing layer (e.g. Bolding et al., 2002; Jeffrey et al., 2008) and permits calculating the turbulence properties, such as turbulent viscosity, tracer diffusivity, (TKE) and TKE dissipations rate.

This one-dimensional model is used to investigate hydrodynamic and thermodynamic processes related to vertical turbulence in natural waters. Furthermore, it is designed in a way that can be easily matched with three-dimensional hydrodynamic models and used to calculate vertical turbulent mixing. GOTM uses the one-dimensional equation to solve momentum, salt and heat transfer equations that are the main elements to solve simulating equations for turbulent fluids. In this research, the turbulence closure scheme, \( k - \varepsilon \) equation is applied.

The study area is located between latitude 26 degrees and longitude 56 degrees in the southern part of the Strait of Hormuz. The measurements, including the profile of temperature and salinity from the surface to a depth of 110 meters were performed at 20-meter intervals continuously from December 1996 to March 1998 according to the Eulerian method by the Miami University. Synoptic meteorological data of 1997 of Qeshm Island were obtained from NOAA website (Table 1), including wind, humidity, cloudiness, air pressure and air temperature at three hours intervals.
3. Results

3.1. Surface forces application as boundary condition

In table 1 all surface forces for simulation boundary conditions are available. In this part of the article, air pressure changes are studied as a boundary condition. Figure 1 shows the rate of air pressure changes during one year in 1997.

As can be seen in Figure 1, air pressure decreases from its highest in January to lowest in July. Then begins rises again until the year end. This process justifies Anti-cyclone formed over the region in the winter and weakened in the summer.

Anti-cyclones are high-pressure centers that air moves centrifugal and downward through them. In warm seasons, a cyclone (low pressure) is governed on the region that shows advection at this time of the year. Formation of these cyclones and anti-cyclones plays an important role in creating winds. Minimum air pressure is in July, rises to 987 hPa. Maximum air pressure governs in late December and hikes up to 1024 hPa. Other meteorological parameters of Qeshm data were analyzed the same way.

Table 1: Dataset used in the model run

<table>
<thead>
<tr>
<th>Data</th>
<th>Data type</th>
<th>Source</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanography</td>
<td>Vertical profile of temperature and salinity</td>
<td>Measured</td>
<td>Simulating</td>
</tr>
<tr>
<td>Meteorological data</td>
<td>Wind, temperature, air pressure and relative humidity</td>
<td>Meteorology websites</td>
<td>Upper boundary conditions, momentum, turbulent heat fluxes and surface radiation budget</td>
</tr>
</tbody>
</table>

![Air pressure graph](image)

Fig. 1: Air pressure changes in 1997

3.2. Model validation

GOTM calibration has been discussed in detail in season 6 (Burchard, 2002). In this research, the time step of the simulation was 120 seconds and 100 layers of water were considered. This model based on layer numbers and time step, determines coefficients to solve \( k - \varepsilon \) second-moment closure scheme in a way that model stays stable. As can be seen, the comparison between simulated temperature and salinity (Figure 3 and 5) and measured temperature and salinity (Figure 2 and 4) show reasonable agreements.
Fig. 2: time variation of observed temperature during 1997

Fig. 3: Simulated temperature for a 1D water column for south of the Strait of Hormuz (1997), modelled with a GOTM
Fig. 4: time variation of observed salinity during 1997

Fig. 5: Simulated salinity for a 1D water column for south of the Strait of Hormuz (1997), modelled with a GOTM.
3.3. Discussion of model output results

3.3.1. Time variation of temperature

Figure (2) shows time variation temperature in intended section in the one-year period of time. As can be seen in this figure, there is no significant temperature variation in the water column in the winter, from December to late May. Water temperature from the surface to the seabed fluctuated between 20 to 25 degrees Celsius. However, a weakly stratified layer from the surface to a depth of 50 meters is observed in this season (Figure 3). From May until the middle of July there are higher temperatures on the surface due to sun’s heat. As a result, water temperature increases to a depth of 40 meters (Figure 2).

The water temperature reaches 27 to 29 °C in this depth. Increase in air temperature at sea level, from July until early October, leads to significant changes in water column temperature. During this period, the water temperature from the surface to a depth of 40 meters is fluctuating between 31.5 to 34 degrees. The layer formed in May, is moved to the depth of 70 meters by the middle of July, approves the formation of seasonal thermocline during this period and the mixed layer extends from the surface to above the thermocline level. From November to December, with a decrease in air temperature, the temperature is reduced in the water column. During this period, the temperature changes 2 degrees (26 to 28 °C) from the surface to a depth of 60m. More in depth, the temperature continues to decrease to the seabed.

3.3.2. Vertical viscosity profile

Figure (6) shows the viscosity changes from the surface to bottom and its relationship with sigma-t and temperature in 1997. Viscosity value is more over the course time from January until early April, following the temperature and sigma-t profile changes due to the cold surface water. From a depth of about 10 meters to 30 meters, the viscosity is between 0.2 to 0.25 m²/s. From 30 to 80 meters depth, with increasing depth, caused raising the pressure, maximum viscosity is between 0.25 m²/s to 0.35 m²/s that proves salty water output of the Persian Gulf through the Strait of Hormuz. Going into the summer it decreases and from mid-May, extends weakly to a depth of 20 meters between the values 0.08 m²/s to 0.12 m²/s. Going into the summer its depth increases with a gentle slope so that in late December, reaches a depth of 60 meters. During this period, less dense water with low salinity entering the gulf has an obvious effect on viscosity value. From November due to lower temperatures and less input water, the viscosity begins to increase.

3.3.3. Vertical profile of buoyancy frequency

Figure 7 shows a comparison of vertical buoyancy frequency profiles (a) with temperature changes (b) during 1997. Vertical buoyancy frequency profiles show the water column stability. The water is unstable up to 50 meters depth from December to early April. However, with increasing depth, the water column becomes stable. No change in buoyancy frequency is observed from early April until early May. As it gets warmer, a layer with a different buoyancy frequency (about 0.005 to 0.0075 l/s²) forms at a depth of 25 meters in early May. With the passage of time and advancing toward the summer, its power increases. In August reaches up to a depth of 47 to 50 meters and starts to undermine and transferred to a depth of 70 meters and then fades. This layer with high stability has a reasonable agreement with the strong seasonal thermocline in the area. Deeper than this layer is so stable. Above this layer, changes follow the thermocline layer and grow deeper with the passage of
Fig. 6: comparison of vertical viscosity (a) with sigma-t (b) and temperature (c) in 1997
time. From mid-September, the value of buoyancy frequency decreases and is determined with the negative value that implies water column instability during the last months.

3.3.4. Turbulent kinetic energy changes (TKE)

The highest value of TKE occurs in March that changes from the surface to depth, between 0.0015 to 0.0036 m²/s, decreasing from surface to the seabed. Until late April TKE exists only up to 50 meters depth. Then there is a sharp decline so that in early May reaches the lowest amount during the period of the year. At this time TKE is observed only to a depth of 20 meters. Since May to late December, the depth of TKE will increase, so that in early July reaches to a depth of 40 meters and to a depth of 50 meters until November. After that, by the end of December, goes into greater depth and reaches to 60 meters. As figure 8 presents, the penetration depth of TKE depends on the penetration depth of buoyancy frequency. As buoyancy frequency determines the stability of the water column, is effective in limiting the penetration depth of TKE. In comparison with a study conducted in the Bay of Biscay (Cabrillo et al., 2011), as surface layer’s salinity increases and its temperature decreases, TKE penetration depth is increased to depths of 150 to 200 m. But due to the formation of seasonal thermocline during the summer, penetration depth is limited only to 30 meters. This is in good agreement with the study of turbulence in the Strait of Hormuz.

4. DISCUSSION AND CONCLUSION

By investigating the prevailing weather conditions and changes in physical parameters during the selected time period, the study was divided into two periods of warm and cold seasons. The results show a more highly stratified water column which is statically stable during a yearlong time.

Fig. 7: comparison of Vertical profile of buoyancy frequency (a) and temperature changes (b) in 1997
During the cold season which includes winter, the air temperature is low. Low air temperature leads to the reduction in surface water temperature (about 22 to 24 °C). This coldness increases the density of saline water. Because of the mixed water, displacements caused by a rise in surface water density and no factor to inhibit diffusion, turbulent kinetic energy covers surface to seabed.

In the surface layer, Turbulent Kinetic Energy (TKE) is dominant which is generated by low quantities of shear production maintained by the surface wind stress in the mixed layer and buoyancy production. In the deep layer, it may be observed that TKE is generated only by buoyancy term. Because due to absence of wind stress there is not shear production, therefore, TKE is generated only by buoyancy term. As shown in figure 8, in the deep layer, turbulent kinetic energy is zero which is related to the absence of shear production in this region and that the buoyancy term is neutral.

Due to the dependency of the turbulent kinetic energy to buoyancy and shear products caused by winds, also stronger tensions caused by wind, turbulent kinetic energy is with the most power and the most impressive result during this period. Most of it appeared in mid-March from surface to a depth of 20 meters between 0.0029 and 0.0037 m²/s² values. Shear products power is decreased with increasing depth; however, turbulent kinetic energy still exists. It shows that turbulent viscosity and buoyancy terms are an agent for turbulence at depths greater than 30 meters.

Due to the arrival of the warm period, the air pressure has the lowest value of 987 hPa in July. The temperature reaches its peak, according to weather reports in August to 39 °C. Due to the increase in temperature, evaporation is increased and humidity reaches its peak in this period. Due to the high temperature and the heat energy absorbed by surface water as it evaporates, the water level reaches its highest temperature during this period. At this time, water enters the Persian Gulf from the Gulf of Oman through the Strait of Hormuz. As the input water from the Sea of Oman increases, Sigma-t varies from surface to a depth of 30 meters with the values fluctuated between 26 and 26.5 kg per cubic
meter. Since the beginning of this period in early May a layer with high buoyancy frequency is formed at a depth of 25 meters. With the passage of time, and progress towards the summer, becomes more powerful, and in August reaches to a depth of 47 m to 50 m and then begins to weaken until the end of December and will be transported to a depth of 70 meters and then fades. The formation of this layer makes the upper part of the water column stable and limits the penetration depth of the turbulent kinetic energy and there is no turbulent kinetic energy at the bottom of this layer, where high-density saline water passes from the Persian Gulf to the Gulf of Oman. As it is clear from the profile results the penetration depth of TKE depends on the buoyancy frequency penetration depth. As Buoyancy frequency determines the stability of the water column, is effective in limiting the penetration depth of TKE. During the winter, turbulent kinetic energy expands from the surface to the seabed and going to summer, the depth of penetration into the layer which has a high buoyancy frequency is limited.

References


www.gotm.net.