

Numerical modelling the effect of wind on Water Level and Evaporation Rate in the Persian Gulf

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ARTICLE INFO

Article History:

Received: 04 Feb. 2021

Accepted: 03 Apr. 2021

Keywords:

Persian Gulf

Water Level

Wind

Numerical modelling

ABSTRACT

Evaporation is one of the most important quantities in the marine climate, and in the Persian Gulf, this parameter makes it one of the saltiest free waters in the world. Evaporation estimation is essential for water balance studies, irrigation, and land resource planning. Persian Gulf is known as shallow water and therefore has a high temperature in summer, which increases the rate of evaporation and high salinity up to 50PPT. In this study, the effect of wind speed and direction on the rate of evaporation in the Persian Gulf, assuming that there is no water inflow into the basin, was investigated using numerical modelling. Mike model is based on the three-dimensional solution of the Navier Stokes equations, assumption of incompressibility, Boussinesq approximation, and hydrostatic pressure. The effects of wind on evaporation at four different wind speeds and four different wind directions have been investigated. Results show the wind direction has little effect on evaporation, but wind speed has significant changes on evaporation rate and water level, and these changes are nonlinearly related to water temperature so that in summer the evaporation rate increases faster with increasing temperature.

1. Introduction

Evaporation estimation is essential for water balance studies, irrigation, and land resources planning. There are different methods for estimating and measuring evaporation rates. These methods can be divided into several categories: 1- Experimental [1], 2- Water budget [2], 3- Energy budget [3], 4- Mass transport [4], 5. Combined [5]. Studies show that meteorological factors such as pressure gradient, wind speed, and temperature have the greatest effect on evaporation. The evaporation rate is calculated using the Bulk method as follows [6]:

$$E = K(e_w - e_a)w \quad (1)$$

Where E is the evaporation in mm/day, $K = 10.137 \times 10^{-2}$, e_w is the saturated vapor pressure at water temperature, and e_a is the vapor pressure at air temperature. These two parameters are calculated as follows [7]:

$$e_a = 6.112 \times \exp\left(\frac{17.67T}{273.15+T}\right) \quad (2)$$

$$e_w = e_a \times \text{relative humidity} \quad (3)$$

The Persian Gulf is semi-enclosed and shallow water that results from continuous deposition in a once-deep basin [8]. The length of the Persian Gulf is about 1000 km in the northwest-southeast direction, the maximum width is 338 km and the minimum width is 56 km in the Strait of Hormuz, which has an approximate area of 3.39×10^5 Km². The coastal topography of the Persian Gulf on the periphery of the countries shows the

following features: While the coasts of Iran are mountainous, the coasts of the Arab countries are mostly flat deserts, except around the Strait of Hormuz, which has a high and rocky topography on the Musandam Peninsula. Depth measurement of the Persian Gulf also shows asymmetry, so that a depression extends from the Strait of Hormuz to the northwest along the coast and a shallow coastal area with a depth of fewer than 20 meters in the southwest of the Persian Gulf (Figure 1). With an average depth of 35 meters and a maximum depth of 110 meters in the Strait of Hormuz, the Persian Gulf bed falls quickly from the Strait of Hormuz without any significant effects and reaches a depth of 2000 meters in 200 kilometers inside the Oman Sea [9].

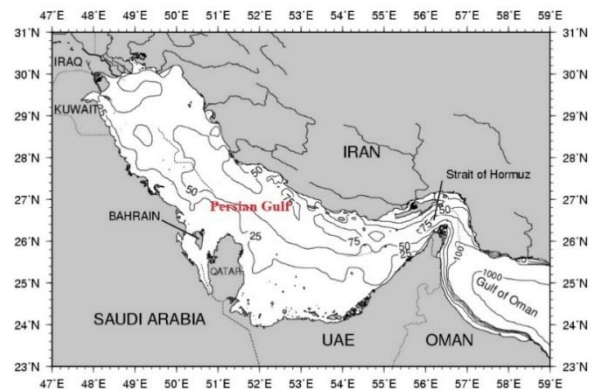


Figure 1. Map of the Persian Gulf region

Persian Gulf water is one of the saltiest bodies of water in the world's oceans. This water comes out of the deep areas of the Strait of Hormuz and creates a kind of reverse estuaries due to the way water is exchanged. As the water leaves the strait, less saline water enters the Persian Gulf from the Oman Sea, diluting it. The outflow waters of the Persian Gulf reach a neutral buoyancy level at depths of 200 to 350 m and are released horizontally as the saltiest groundwater in the North Indian Ocean [10, 11, 12, 13]. The waters of the Red Sea and the Persian Gulf together provide high salinity intermediate waters at 900 m above the Indian Ocean [11]; thus, similar to other sub-marine and marginal seas such as the Red and Mediterranean Seas, the Persian Gulf, as a dense basin, is responsible for supplying subsurface saline waters in the open oceans. Due to the region's high air temperatures and its arid climate, evaporation in the Gulf is high. Previous studies on heat fluxes in the Persian Gulf provide mixed answers for the amount as well as times of maximum and minimum evaporation rates in the Gulf. There are several studies of heat fluxes in the Persian Gulf. Privett reported maximum evaporation rates of 0.0036 Sv (1 Sv = 106 m³/s) in December and minimum rates of 0.00049 Sv in May with an annual-mean evaporation rate of 0.011 Sv [14]. Hastenrath and Lamb used a climatic atlas of the Indian Ocean and estimated monthly evaporation rates for the Persian Gulf [15]. The values as well as the time of occurrence of maximum and minimum evaporation estimated by these authors are in agreement with Privett. According to these authors, evaporation of 29.3 cm/month occurs in June and a minimum value of 8.1 cm/month is found in February, with an annual mean of 20.16 cm/month for that area. Xue and Eltahir estimate that the Gulf acts as a sink of heat for the atmosphere (+3 W/m²) and the annual evaporation from the Gulf is 1.84 m/yr [16].

It is difficult to consider all the components affecting evaporation in the hydrological cycle, to study their effects and the extent of the impact of each. In this study, the effect of wind speed and direction on the rate of evaporation in the Persian Gulf is investigated, assuming that there is no water inflow into the basin.

Because observational data are limited, previous estimates of water and heat budgets are highly uncertain. This large defect has attracted the attention of climatic and hydrological studies. The values of previous studies related to surface heat flux from incoming flux + 66 W/m² to the lost flux-21 for the Persian Gulf have been reported. This uncertainty leaves many questions and causes the water exchange rate to be reported from 1.4 to 2.1 m/year. As shown in relation (1), one of the factors affecting evaporation is wind speed, which changes the rate of evaporation linearly, but when these changes are accompanied by a change in temperature according to relations (2) and (3), it will become nonlinear. In other words, the effect of wind in different seasons causes the evaporation rate

to be different. In this study, the effect of wind speed and direction on the change of water level and evaporation rate due to seasonal changes in temperature will be investigated.

The evaporation rate directly affects the salinity of the Persian Gulf, which is one of the most important and influential parameters in the circulation of the Persian Gulf. The circulation in the Persian Gulf is a cyclonic circulation that is primarily caused by the density difference between the Gulf of Oman and the Persian Gulf, and this density difference is affected by the salinity difference between the two basins [17, 18, 19]. In oceanic numerical modeling, evaporation is usually considered as an input in the form of latent heat flux. Therefore, accurate determination of this parameter leads to more accurate modeling results. On the other hand, direct measurement of evaporation is impossible due to the exchange of Persian Gulf water with the Oman Sea and the data of meteorological stations near the Persian Gulf cannot be cited because the mechanism of measuring evaporation in these stations is different from how seawater evaporates, And only perhaps can seasonal variations of this data be cited under certain conditions.

2. Method

Equations In this research, JEBCO topography data with an accuracy of about one kilometer have been used. Then, in the Mesh Generator section of Mike software, an irregular and triangular computational network of 10699 elements and 6196 nodes were created (Figure 2). The boundaries of the study area were considered as land boundaries to prevent water from entering the basin. Therefore, the equations are solved by considering the heat-salinity forces and wind stress and without considering the tide. In models that are implemented with one of the finite element numerical methods or finite difference, the stability and convergence of the model depend on characteristics such as time step, the distance of network nodes, etc. In the hydrodynamics module of the MIKE program, the CFL condition is also used for stability, which is as follows:

$$CFL = (\sqrt{gh} + |u|) \frac{\Delta t}{\Delta x} + (\sqrt{gh} + |v|) \frac{\Delta t}{\Delta y} \quad (4)$$

Because the network used in the model is an unstructured network, the dimensions of each network cell are different, so the time step used to calculate the CFL value is between 0.01 and 30 seconds. Also, the critical CFL value is set to 0.8, and if the calculated CFL values for each of the network cells exceed this value, the model will crash. It should be noted that the critical CFL value is based on the default of the model and its value is determined by considering the highest flow velocity that can be observed in the seas. If the CFL value for all cells is less than 0.8 during the model run, the stability condition is met.

Mike model uses the following equations to calculate evaporation. The latent heat can be written as [20]:

$$q_v = -P(a_1 + b_1 W_{2m}) \exp\left(K\left(\frac{1}{T_k} - \frac{1}{T_{water}+T_k}\right)\right) \cdot \left(\frac{T_{water} + T_k}{T_{air} + T_k}\right) R \cdot \exp\left(K\left(\frac{1}{T_k} - \frac{1}{T_{air}+T_k}\right)\right) \quad (5)$$

Where $P_v=4370 \text{ J}\cdot\text{K}/\text{m}^3$, $K=5418^\circ\text{K}$, R is relative humidity, $T_k=273.15^\circ\text{K}$ is the temperature at 0°C , T_{water} and T_{air} are the temperatures water and air respectively. During cooling of the surface the latent heat loss has a major effect with typical values up to $100 \text{ W}/\text{m}^2$.

The wind speed, W_2 , 2 m above the sea surface is calculated from the wind speed, W_{10} , 10 m above the sea surface using the following formula: assuming a logarithmic profile the wind speed, $u(z)$, at a distance z above the sea surface is given by

$$u(z) = \frac{u_*}{\kappa} \log\left(\frac{z}{z_0}\right) \quad (6)$$

Where u_* is the wind friction velocity, z_0 is the sea roughness and $\kappa=0.4$ is von Karman's constant. u_* and z_0 are given by

$$z_0 = \frac{Z_{Charnock} u_*^2}{g} \quad (7)$$

$$u_* = \frac{\kappa u(z)}{\log\left(\frac{z}{z_0}\right)} \quad (8)$$

Where $Z_{Charnock}$ is Charnock parameter. The default value is $Z_{Charnock}=0.014$. The wind speed, W_2 , 2 m above the sea surface is then calculated from the wind speed, W_{10} , 10 m above the sea surface by solving Eq. (7) and Eq. (8) iteratively for z_0 with $z=10\text{m}$ and $u(z)=W_{10}$. Then W_2 is given by

$$W_2 = W_{10} \frac{\log\left(\frac{2}{z_0}\right)}{\log\left(\frac{10}{z_0}\right)} \quad W_{10} > 0.5\text{m/s} \quad (9)$$

$$W_2 = W_{10} \quad W_{10} \leq 0.5\text{m/s}$$

The heat loss due to vaporization occurs both by wind driven forced convection by and free convection. The effect of free convection is taken into account by the parameter a_1 in Eq. (5). The free convection is also taken into account by introducing a critical wind speed $W_{critical}$ so that the wind speed used in Eq. (9) is obtained as $W_{10}=\max(W_{10}, W_{critical})$. The default value for the critical wind speed is 2 m/s .

Table 1 shows the different scenarios that have been considered. The effects of wind on evaporation at four different velocities and four different wind directions have been investigated. The accuracy of the model results is checked based on the change of water level under standard conditions. The prevailing wind in the Persian Gulf, according to most studies [21, 22], is the Shamal wind, which blows from the northwest during the year, and the speed of 5 meters per second is the average speed that can be considered for this wind during a year. Implementation of the model taking into account these conditions should lead to a reduction of 1.3 to 2.2 meters of water level due to evaporation in

the Persian Gulf, as mentioned in previous studies [22]. Therefore, if under these special conditions the amount of evaporation or reduction of Persian Gulf water is in this range, we can ensure the accuracy of the results obtained. Of course, it must be said that because evaporation is usually one of the input parameters of models, in some modelling is considered as a variable parameter; That is, it must be corrected to lead to temperature and salinity output with minimal error.

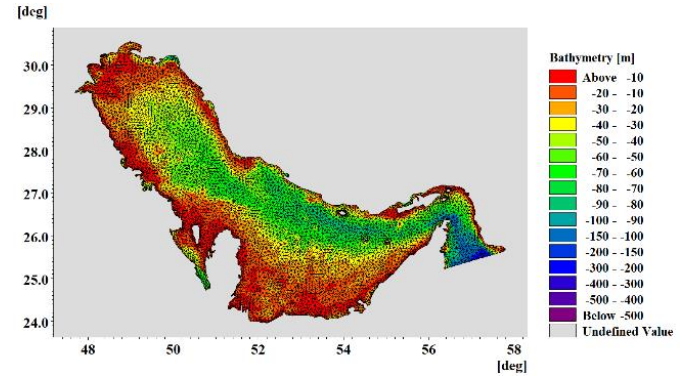


Figure 2. The network used in the model

Table 1. Different scenarios to investigate the effect of wind on evaporation

Dependent Variable	Independent Variables		
	Number of Test	Wind Speed (m/s)	Wind Blowing Direction (deg)
Evaporation	1	5	270
	2	5	0
	3	5	90
	4	5	180
	5	8	270
	6	2	270
	7	12	270

3. Results and Discussion

The output of the model including evaporation rate and water level at three different points in the basin has been studied under different scenarios. The coordinates of these three points are specified as stations 1, 2, and 3 in Figure 3. Figure 4 shows the water level changes due to the change in wind direction. As can be seen, the change in wind direction did not have a significant effect on the change in water level, and for all directions, the water level decreased by more than two meters during the year. Figure 5 also shows the changes in evaporation rate per change of wind direction, and as we see in stations 1 and 2, there is no significant difference between changes in evaporation rate per change of wind direction, but in station 3 at the end of the one-year period there is little difference. It exists between different directions and has a higher evaporation rate per 180° wind angle. As can be seen, the water level has decreased by approximately 2.2 meters during one year of the model running. Although this value is within the allowable

range, it seems that the average speed of 5 m/s throughout the year causes maximum evaporation, which can be better judged by the results that are examined at different speeds. Note that the model of Kampf and Sadrinasab has an evaporation rate of 1.8 m/year that is larger than observations [17]. The rate of evaporation minus precipitation in the modeling study of Yao and Johns (from 1.2 to 1.43 m/year) [23]. In studies about the investigation of evaporation in water basins, as well as the equations that exist to calculate evaporation, only wind speed is considered and wind direction has no role. In the results of this section, the effects of wind direction change on evaporation are not observed and the reason is that the distinction between different wind directions is not included in the model evaporation calculations. However, physically, basins such as the Persian Gulf, which are limited to the mountainous areas in Iran from the north and to the desert areas in Saudi Arabia from the south, have different wind directions that transfer moist air masses to different areas. This can be accompanied by a change in relative humidity over the water basin.

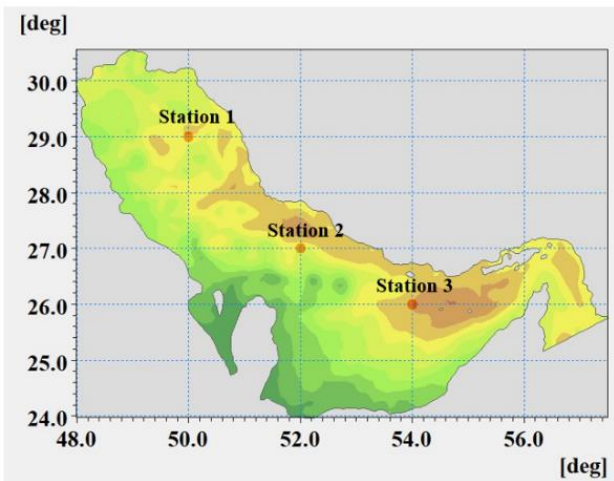


Figure 3. Location of Stations

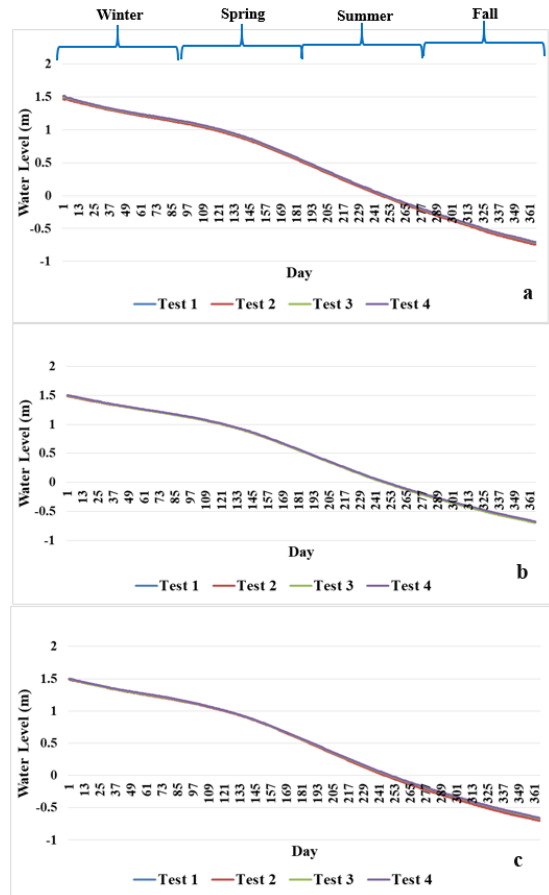


Figure 4. Water level changes due to the change in wind direction at (a) station 1, (b) station 2, (c) station 3

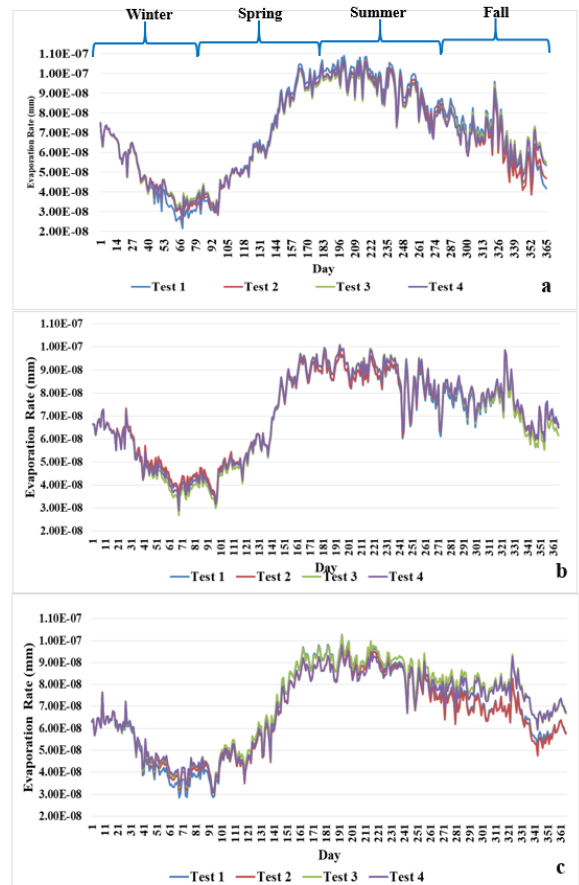


Figure 5. Evaporation rate changes due to the change in wind direction at (a) station 1, (b) station 2, (c) station 3

Figure 6 shows changes in water level due to changes in wind speed. Contrary to the wind direction, wind speed has a significant effect on water level, so that by increasing the wind speed from 2 to 12 m/s, the water level decreases by about 4 times. Figure 7 shows the changes in evaporation rate due to changes in wind speed, and it can be seen that in winter, when the surface water temperature is low, the change in wind speed has no significant effect on changes in evaporation rate, but in summer with increasing Water surface temperature, evaporation rate has increased significantly with increasing wind speed. Figure 8 also shows the surface temperature in winter and summer and shows that the temperature difference in most places is more than 10 degrees. the SST is as much a reflection of the surface flux as being a forcing of the flux in a shallow water system, the high-frequency variability of the SST must be resolved (using a coupled model) to be consistent with the response time scale of the local air–sea feedback process, otherwise systematic biases may occur [24].

Yu and Weller analyzed the trend relationship between latent evaporation and SST using the OAFux products. They found that the linear trend patterns in the two variables are very similar, suggestive of the atmospheric response to oceanic forcing. Also they reinforced the notion that the relationship between evaporation, wind speed and humidity is nonlinear and that SST is a forcing for changes in evaporation [25]. In Figure 8, the nonlinearity of the evaporation rate with the wind speed can be seen well, and according to the temperature change due to the change of seasons, temperature increase can be considered as a stimulus to increase evaporation.

Yu examined the role of wind speed change in global changes in ocean evaporation. Using EOF analysis, he examined the yearly winter-mean time series of evaporation and related air-sea variables such as wind speed and humidity. The results showed the dominant role of wind force in evaporation and humidity. He hypothesized that the effect of wind on evaporation takes place in two ways. The first way is direct: the greater wind speed induces more evaporation by carrying water vapor away from the evaporating surface to allow the air–sea humidity gradients to be reestablished at a faster pace. The second way is indirect: the enhanced surface wind strengthens the wind-driven subtropical gyre, which in turn drives a greater heat transport by the western boundary currents, warms up SST along the paths of the currents and extensions, and causes more evaporation by enlarging the air–sea humidity gradients [26].

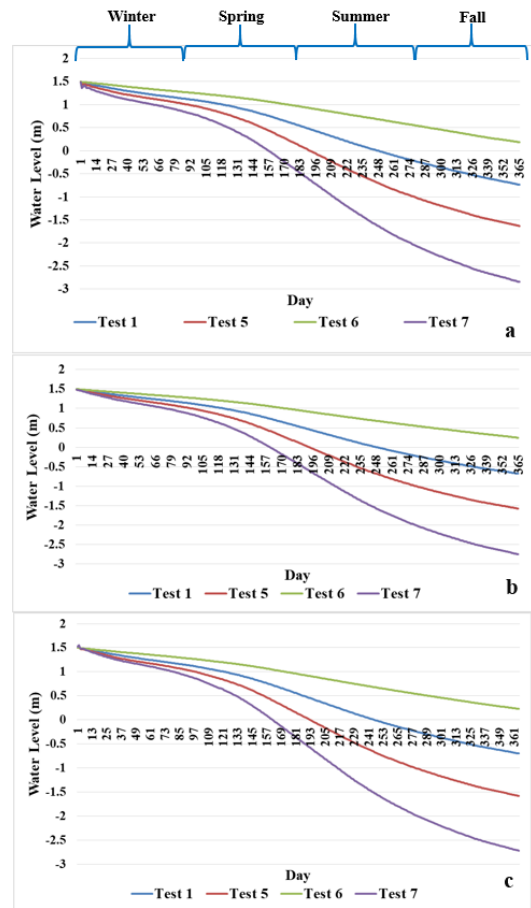


Figure 6. Water level changes due to the change in wind direction at (a) station 1, (b) station 2, (c) station 3

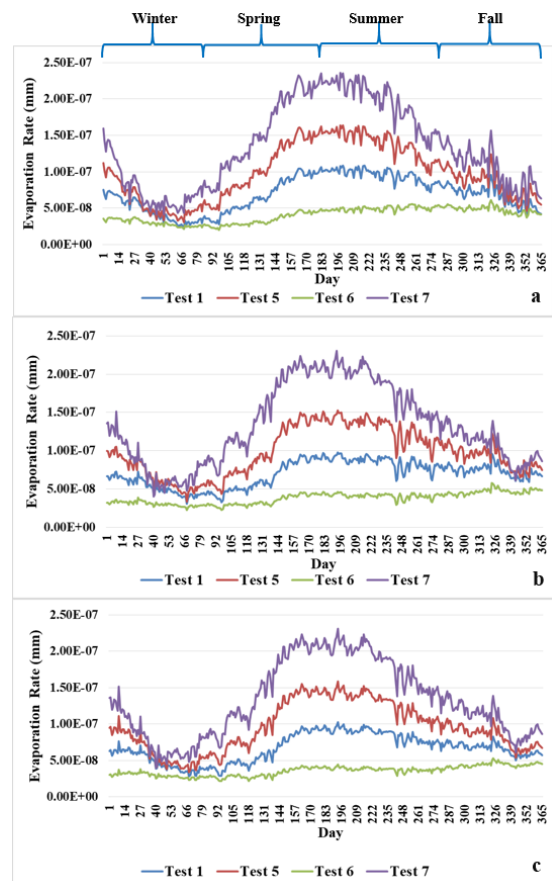


Figure 7. Evaporation rate changes due to the change in wind direction at (a) station 1, (b) station 2, (c) station 3

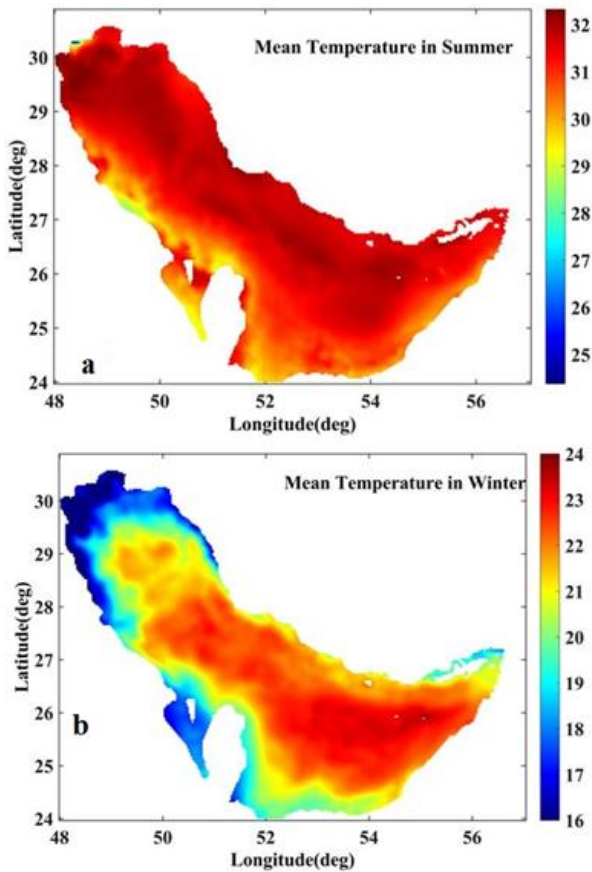


Figure 8. Sea surface temperature in (a) Summer, (b) Winter

4. Conclusions

Comparison of all figures shows that wind direction changes have no effect on evaporation rate and water level and its effects are very small; However, changes in wind speed have a great effect on evaporation rate and water level, especially in summer with increasing water temperature, increase in evaporation rate and the effect of wind speed is more, and this shows that changes in evaporation rate with wind speed are nonlinear. The decrease in water level also increases with increasing temperature and this parameter is also nonlinear and the higher the wind speed, the higher the rate of evaporation and decrease of water level.

Evaporation is one of the most important quantities in the maritime climate, and in the Persian Gulf, this parameter has made this basin one of the saltiest open waters in the world. Evaporation depends on factors such as air temperature, wind, relative humidity, cloud cover, etc. In this study, the effects of wind including wind speed and direction on evaporation rate during one year were investigated. The results showed that the wind direction has little effect on evaporation but wind speed has significant changes on evaporation rate and water level and these changes are nonlinearly related to water temperature so that in summer the evaporation rate grows faster with increasing temperature. Of course, perhaps the reason why the wind direction effects were not well defined is that the model only simulated marine parameters. To investigate the effect of wind direction, it is better to couple the oceanic

model with a meteorological model and include a wider area including the areas around the Persian Gulf in the modelling basin. Past studies on evaporation rates have shown conflicting results from time to time; in other words, some researchers have found that evaporation rates are higher in summer and others in winter. However, in the study of Xue and Eltahir, the highest evaporation rate was obtained in November, although the summer average is higher than the winter [16].

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