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Calculation of sea surface drag coefficient and wind stress in the Gorgan Bay

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Abstract

In this study, considering the closed basin Gorgan Bay which is marine ecologically important, and the information and data available in the region, the wind stress in the bay, is calculated taking into account the drag coefficient. Wind stress is one of the important factors in water circulation and the exchange of energy between air and sea. By studying different parameters affecting wind stress such as wind speed and local drag coefficient, the wind stress and drag coefficient were calculated based on the data of Meteorological Organization. Also, the stress due to rainfall in the bay was calculated and investigated. The results show that the average drag coefficient and wind stress in the Gorgan Bay in 2008 were 1.66×10^{-3} and 0.37 N/m^2, respectively, which should be considered in the pattern of water circulation and more precise calculations of sea level for designing of marine structures.

Keywords: Gorgan Bay; Wind Stress; Drag coefficient; Rainfall.

1. Introduction

Today, the sea surface drag coefficient is very important in calculating the momentum transfer rate from atmosphere to ocean or in other words wind stress. The wind stress creates a major link between ocean and atmosphere and plays an important role in controlling energy exchange between them.

A relationship was established for the sea surface drag coefficient in terms of wind speed by Yelland and Taylor (1996). In addition, Bye proposed a boundary layer model to investigate the sea level drag coefficient under the influence of severe winds (Bye and Jenkins, 2005).

Kara (1999) obtained the drag coefficient in

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terms of wind speed and air-sea temperature difference, which is highly accurate and suitable for different areas. The calculation of wind stress (in the Arabian Sea) was also compared through different methods; mathematical relationships, oceanographic and atmospheric models, buoys, and satellites.

The major processes affecting the surface of the seas and oceans occur in the Troposphere, which extends from the earth's surface to an altitude of 11 km. Most meteorological data are used to estimate surface winds in marine areas in this layer. The lower part of the troposphere is called the atmosphere or planetary boundary layer, in which the winds are affected by the surface of the earth. The thickness of this boundary layer is less than 2 km.

Generally, the heat fluxes and wind stress at the air-sea interface create the main link between the ocean and the atmosphere, and these quantities are important in controlling the energy exchange between the two systems. In ocean circulation patterns, wind stress is considered to be the main driver for the upstream ocean flow at a specific scale, and air-sea flux, which is a source of energy transfer between the air and the sea, is one of the key climatic processes that have a significant impact on air and sea circulations. This phenomenon affects on the distribution of temperature and rainfall in both the time scale and the spatial scale from equator to pole in global and regional dimensions. In order to determine the energy exchange of the oceans, accurate calculation of these energy fluxes is necessary, which in some areas reaches to dozens and hundreds W/m^2. Despite the difficulty of installing, storing and retrieving accurate and long-term measurements in the oceans, there are significant numbers of such observations in ocean reference stations (Hutto *et al*., 2004) and tropical moored buoys (McPhaden *et al*. , 2010). Considering the importance of calculating as accurately as possible the values of fluxes transmitted between the air and the ocean and its role in recognizing the performance of the physical and hydrodynamic phenomena of the sea, this part of the oceanographic studies has an essential role.

The momentum flux is one of the most important fluxes of atmospheric boundary layer on the sea surface, which directly affects on the wave height. The formation of waves at the surface will change the roughness height of the sea surface, which will change the frictional velocity values, and subsequently the characteristics of the boundary layer (Andreas, 2004). More researchers believed that the decrease in the momentum exchange in the velocities above 30 m/s is due to the formation of ocean spray. In the case of wind speeds of 7 - 20 m/s, the sea surface drag coefficient depends not only on the wind speed, but also on the wave status (Liu *et al*., 2012). Powell *et al*. (2003) obtained a relationship between the sea surface drag coefficient and wind speed at high wind speed conditions and found that when the wind speed exceeds of 33 m/s, the sea surface drag coefficient decreases with wind speed. Yelland and Taylor (1996) established a relationship between sea surface drag coefficient and wind speed. Bye and Jenkins (2005) proposed a boundary layer model to investigate the sea surface drag coefficient under severe winds. Kara (1999) obtained the drag coefficient in terms of wind speed and air-sea temperature difference, which is highly accurate and suitable for different areas. It also compares the calculation of wind stress (in the Arabian Sea) through the mathematical relationships and the atmospheric-ocean models using buoys and satellites.

2. Materials and methods

In this research, the water surface drag coefficient and wind stress are monthly calculated in Gorgan Bay for 2008, based on the latest presented formulas and using the required data from various research centers, such as the Iran Meteorological Organization, the Ministry of Energy Water Research Institute, and etc.

Gorgan Bay with an approximate length of 50 km, a maximum width of 12 km and an area of more than 400 km^2 is located in the southeast of the Caspian Sea and is in the form of a triangle which its head geographically is placed in westward (Figure 1). The maximum depth of 6.5-7 meters is reported at the bay center. Gorgan Bay is located in longitudes of 53º 30´-54º 03´ E and latitudes of 36º 47´-36º 54´ N. There are no considerable rivers in the Gorgan Bay due to specific hydrological and geological characteristics, and only the Gharehso River has permanent water that leads to the bay. The estimated average annual amount of water that flows to the Gorgan Bay and the Caspian Sea is 2.9m^3/s, and about 63million m^3/y. Due to the lack of existence of tides in the Caspian Sea, tidal issues have not important roles in the bay. The general circulation of water in the Caspian Sea can flow through the northeast open border of the bay, which the water exchange is caused the heat transfer to the bay. The water density is estimated about 700m^3/s.

In the designing of surface and submarine vessels with aerodynamic shape, the force from the water to the vessels is divided in two components; parallel to the flow and the other perpendicular to the flow, which the force component acting opposite to the relative motion of the vessel moving relating to the surrounding fluid is called drag force. Determining the drag force on the vessel that is exposed to fluid motion is difficult, because the drag force depends on different factors such as the transition from calm flow to turbulent flow in the border line and separation location, and so on. Therefore, they often have to use experimental data and for this purpose, the drag force is usually expressed with following formula (Shames, 2003):

$$F_D = C_D A \frac{\rho V_0{}^2}{2} \qquad (1)$$

which, C_D is drag coefficient, A is usually the surface plotted along the current, V_0 is free stream velocity, and ρ is the water density. For

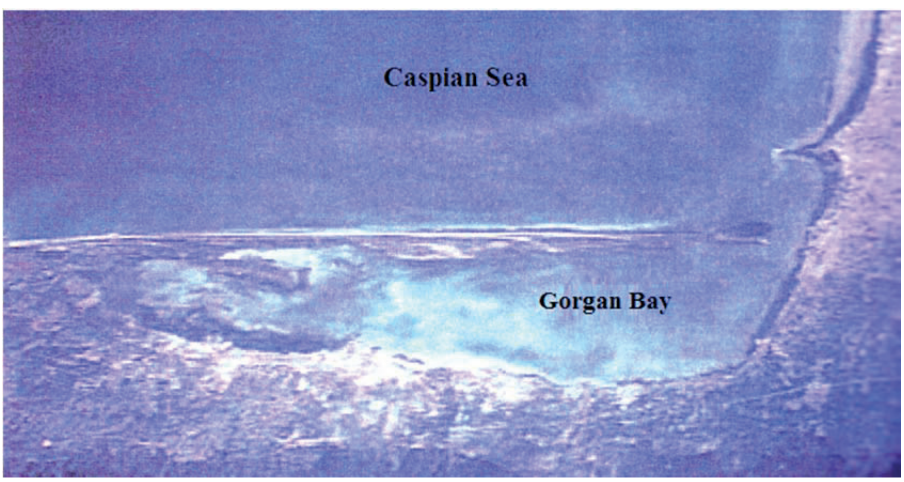

Figure 1. Satellite Image of the Gorgan Bay (Sabet Ahd Jahromi, 2017)

the plates parallel to the currents with a length of l, and width of b, A is the real area of the plate. The Drag Coefficient (C_D), which is the dimensionless are calculated from Equation (1) as follows (Shames, 2003):

$$C_D = 2\left(\frac{F_D / A}{\rho V_0^2}\right) \quad (2)$$

The sentence in brackets is called the Euler number, which is the ratio of the pressure force to the inertia force.

$$\text{Euler number} = \frac{\Delta P / L}{\rho V^2 / L} = \frac{\Delta P}{\rho V^2} \quad (3)$$

In low-speed currents around immersed objects in the fluid, the only non-dimensional number other than the Euler number is the Reynolds number which is calculated from Equation (4) by dividing the inertial force to frictional force.

$$\text{Reynolds number} = R_e = \frac{\rho V^2 / L}{\mu V / L^2} = \frac{\rho V L}{\mu} \quad (4)$$

In this regard, L is the proper size of the body immersed in the fluid. Therefore, for a given Reynolds number, the drag coefficient (C_D) is the same for all similar dynamical flows. If the surface of the object in the fluid is parallel to the flow, the drag is only due to shear stresses. But if it is perpendicular to the flow, it is only due to tensile stresses. Therefore, the drag coefficient (C_D) includes of the pressure drag caused by vertical stress and surface drag caused by shear stress. Figure 2 shows variations of C_D in different angle (α) relative to a flat plane.

In terms of the drag coefficient in the boundary layer (air-sea), it is clearly dependent on the wind speed, because the wind velocity near the ground corresponds to the stability of the atmosphere and is calculated as follow (Coastal Engineering Manual, 2006).

$$U_Z = \frac{U_*}{K} Ln\left(\frac{Z}{Z_0}\right) \quad (5)$$

which, U_Z is the wind speed at Z height above the water, U_* is the frictional velocity of the wind at sea level, Z_0 is the surface roughness height, and K is the constant coefficient of von Karman that approximately is equal to 0.4. The wind stress at the water surface or the momentum transfer rate from atmosphere

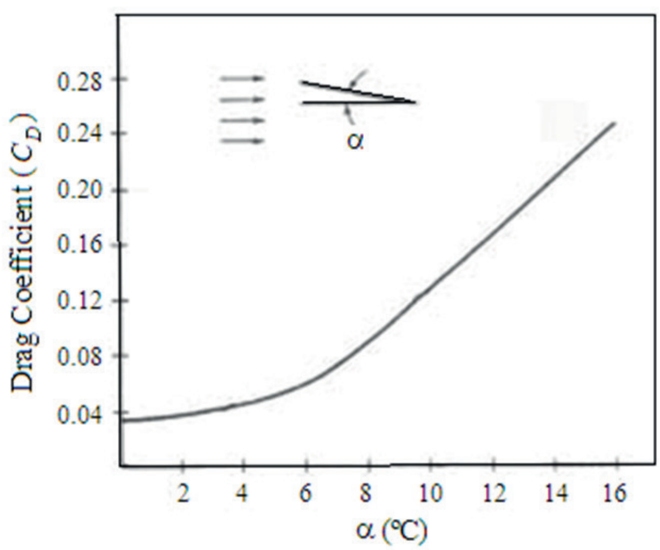

Figure 2. Drag coefficient for a flat plane in angle (Stewart, 2005)

to water column can be written as follows (Coastal Engineering Manual, 2006).

$$\tau = \rho_a {U_*}^2 = C_{DZ} \rho_a {U_Z}^2 \tag{6}$$

which, τ is the wind stress, ρ_a is the air density, and C_{DZ} is the drag coefficient for the winds measured at the Z altitude that this height is 10 meters above the ground level in accordance with the International Standards. If wind velocities are measured at 10-m height, the Z letter is removed from the subscript and the wind stress is obtained as follows (Stewart, 2005; Kara, 1999; Coastal Engineering Manual, 2006).

$$\tau = \rho_a C_D U_{10}^2 \tag{7}$$

Many evidence suggests that the drag coefficient (C_D) on the sea depends on wind speed. Meanwhile, when the sea level or the dryness is much warmer or colder than its top air, the thermal stability effects have a desire to change the logarithmic profile of Equation (5) so that if the atmosphere is colder than the air below, the atmosphere is stably layered and congestion and turbulence transitions are affected and diminished. Furthermore, if the atmosphere is warmer than air, it becomes unstable and turbulences are increased, which the wind speed near the earth surface can be obtained from the following equation (Coastal Engineering Manual, 2006).

$$U_Z = \frac{U_*}{K}\left[\ln\left(\frac{Z}{Z_0}\right) - \varphi\left(\frac{Z}{L}\right)\right] \tag{8}$$

which, φ is a constant global simulation that determines the effects of thermal layering, and L is the length quantity that shows the relative resistance of these effects, which is called Monin–Obukhov length durability. The amount of L for layering in different states: stable, unstable, and neutral is respectively positive, negative, and infinite.

2.1. Drag coefficient on the sea level

The momentum transfer from atmosphere to water can be directly affected by the stability, therefore at the reference level ($Z = 0\ m$) the drag coefficient is obtained from two Equations (6) and (8) (Coastal Engineering Manual, 2006).

$$C_{DZ} = \left(\frac{U_*}{U_Z}\right)^2 = \left[\frac{k}{\ln\left(\frac{Z}{Z_0}\right) - \varphi\left(\frac{Z}{L}\right)}\right]^2 \tag{9}$$

Choosing the reference level at a height of 10-m above the ground, the sea level drag coefficient is obtained from the following equation (Coastal Engineering Manual, 2006):

$$C_D = \left(\frac{U_*}{U_{10}}\right)^2 \Rightarrow C_D = 0.001(1.1 + 0.035 U_{10}) \tag{10}$$

In the 1980, the following formula was proposed by Smith for the sea level drag coefficient in a reference level of 10 meters (Stewart, 2005):

$$1000 C_D = 0.44 + 0.063 U_{10} \tag{11}$$

In addition, other relationships were represented by Yelland and Taylor for the sea level drag coefficient in the reference level of 10-m as follows (Stewart, 2005):

$$1000 C_D = 0.29 + 3.1/U_{10} + 7.7/U_{10}^2 \quad (3\,m/s \le U_{10} \le 6\,m/s) \tag{12}$$

$$1000 C_D = 0.60 + 0.070 U_{10} \quad (6\,m/s \le U_{10} \le 26\,m/s) \tag{13}$$

Since φ is positive for stable conditions, and negative for unstable conditions, the layering process clearly would decrease the drag coefficient for stable conditions and increase

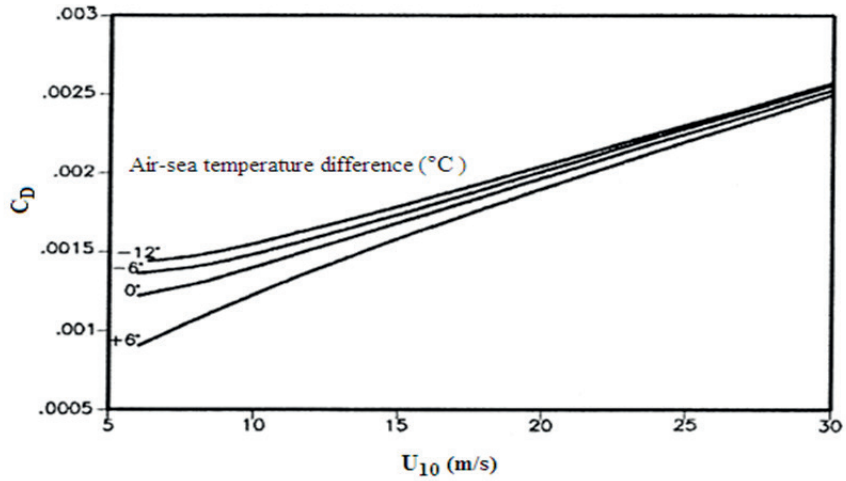

Figure 3. Drag coefficient variations by the wind speed (Coastal Engineering Manual, 2006)

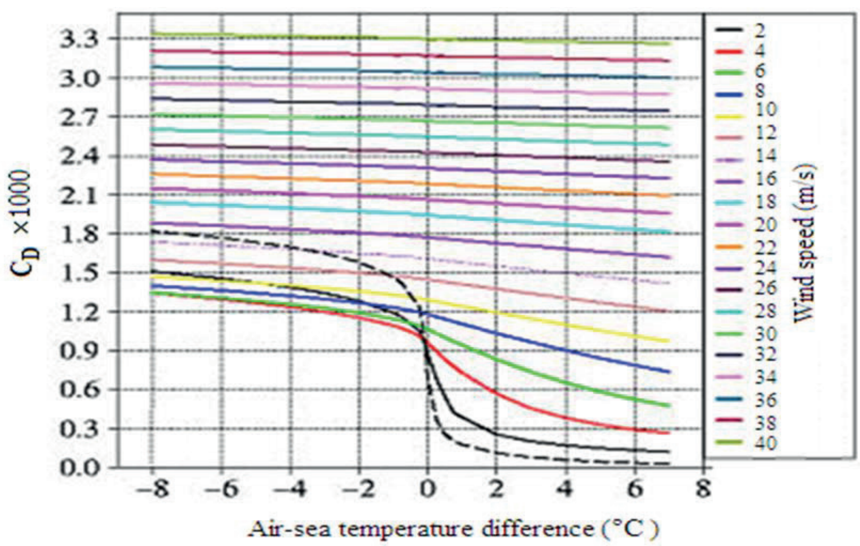

Figure 4. Drag coefficient variations in terms of wind speed and air-sea temperature difference (Kara, 2005)

the unstable conditions. Figures 3 and 4 illustrate the variations of drag coefficient.

3. Results and Discussion

For the constant wind speed, at a reference level of 10 meters, the momentum transmission in the stable atmosphere is less than one in the unstable atmosphere. Based on studies, it is stated that the drag coefficient depends not only on the wind speed, but also on the stage of wave development and air-sea temperature difference. The physical mechanism of this phenomenon is that the phase speed of waves in vicinity of the spectral peak is proportional to the wind speed. At present, sufficient information is not available for a definitive diagnosis of this behavior, and future studies seem to further highlight these effects and their importance in coastal and offshore winds. In

Table 1. Drag coefficient $C_D \times 10^3$ in terms of wind speed and air-sea temperature difference (Kara, 1999)

Air-sea temperature difference (ºC)	Wind speed at 10 meters above sea level (m/s)							
	<5	5-10	10-15	15-20	20-25	25-30	30-35	>35
$T_a - T_s < -5$	1.80	1.86	2.10	2.32	2.48	2.64	2.80	3
$-5 \le T_a - T_s < -1$	1.56	1.78	2	2.25	2.44	2.63	2.80	3
$-1 \le T_a - T_s < -0/2$	1.32	1.60	1.90	2.22	2.42	2.62	2.80	3
$-0/2 \le T_a - T_s < 0/2$	1.20	1.54	1.87	2.16	2.40	2.60	2.80	3
$0/2 \le T_a - T_s < 1$	0.98	1.43	1.80	2.10	2.35	2.57	2.80	3
$1 \le T_a - T_s < 5$	0.60	1.30	1.72	2.04	2.30	2.54	2.79	3
$T_a - T_s \ge 5$	0.06	0.77	1.47	1.95	2.26	2.52	2.78	3

Table 1, the drag coefficient is calculated in terms of wind speed and air-sea temperature difference, which is highly accurate and suitable for different marine basins.

Table 1 shows that the drag coefficient at sea level is directly related to the wind speed, but its dependence on the air-sea temperature difference is higher at lower velocities, so that with increasing wind speed, the dependence of the drag coefficient to the air-sea temperature difference becomes less until the speeds above 35 m/s, the dependency is eliminated. The sea level drag coefficient values in Table 1 were obtained by Kara method which is based on the wind speed and air-sea temperature difference, and has proper accuracy and is suitable for ocean basins.

3.1. Drag coefficient calculation in Gorgan Bay (C_D)

Equations (10), (11), (12) and (13) have been formulated to calculate the sea level drag coefficient. Herein, three equations (10), (11) and (13) are used to calculate the drag coefficient in the Gorgan Bay, but the equation (12) is not applicable in the study area regarding to the wind speed. So that using the values of the fastest wind speed (U_D) measured by the m e teorological organization, the drag coefficient values are determined for different months of 2008 in the Gorgan Bay (Table 2).

Accordi n g to Table 2, the average value of sea level drag coefficient in Gorgan Bay with Equation (11) is equal to , with Equation (13), is equal to, and with Equation (10) is equal to. Also, the total average value of sea level drag coeffic i ent in Gorgan Bay for 2008 is equal to. Th e formula presented by the US Navy's Naval E ngineering Department showed more suitab l e value for calculating the sea level drag c o efficient in the Gorgan Bay, because, the difference between total average value and the me a n value from Equation (10) is lowest than th e ones from two other equations. Drag coeffi c ient is one of the effective factors in wind stress and Table 1 and Figures (3) and (4) indicate that the drag coefficient depends on the air-sea temperature difference and wind speed.

Table 2. Wind speed and drag coefficient values in Gorgan Bay (2008)

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
$U_{10}\ (\frac{m}{s})$	9.3	14.8	13.7	16	10.5	12.7	11.5	8.5	8	17	15	21.5
$C_D \times 10^3$ Smith	1.02	1.37	1.30	1.45	1.10	1.24	1.16	0.97	0.95	1.51	1.40	1.80
$C_D \times 10^3$ Yelland	1.25	1.63	1.56	1.72	1.33	1.48	1.40	1.20	1.16	1.79	1.65	2.10
$C_D \times 10^3$ US Army	1.42	1.61	1.58	1.66	1.46	1.54	1.50	1.39	1.38	1.70	1.62	1.85
$C_D \times 10^3$ Kara	1.78	1.90	1.87	1.90	1.90	1.62	1.52	1.78	1.60	2.15	2.10	2.32

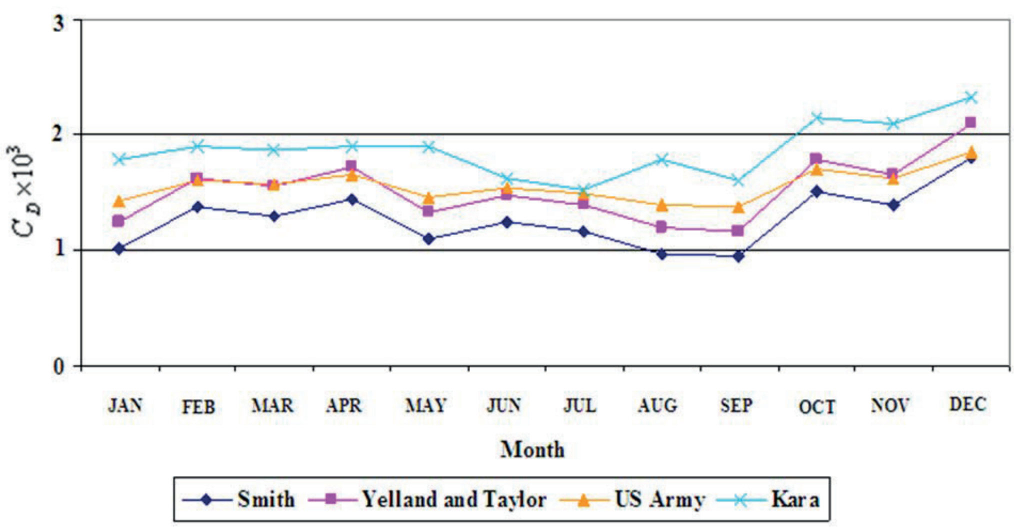

Figure 5. Sea level drag coefficient in Gorgan Bay (2008)

3.2. Calculation of wind stress in the Gorgan Bay (τ)

The effect of wind stress on the sea level is considered as the main factor in the boundary layer. The boundary layer is adjacent to the air-sea interface, which reacts directly to surface forces. This layer shows important seasonal changes that play a major role in the transmission of momentum, humidity and heat, between air and sea. Changes in this layer depend on the air-sea interaction, which can determine the layer depth and its physical properties. The wind stress has the greatest effect on the mixed layer and is one of the most important factors in controlling fluctuations in water level, sea surface temperature changes, and the exchange of momentum and energy from atmosphere to sea. The following formula was used to calculate the wind stress in Gorgan Bay (Stewart, 2005; Kara, 1999).

$$\tau = \rho_a C_D U_0^2 \tag{14}$$

Table 3. Parameters required for calculating wind stress in the Gorgan Bay in 2008

Month / Parameters	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
$\rho_a\ ({kg}/{m^3})$	1.26	1.25	1.24	1.22	1.20	1.18	1.17	1.16	1.18	1.21	1.23	1.26
$C_D \times 10^3$	1.42	1.61	1.58	1.66	1.46	1.54	1.50	1.39	1.38	1.70	1.62	1.85
$U_{10}({m}/{s})$	9.3	14.8	13.7	16	10.5	12.7	11.5	8.5	8	17	15	21.5
$\tau\ ({N}/{m^2})$	0.154	0.440	0.367	0.518	0.193	0.293	0.232	0.116	0.104	0.594	0.448	1.077

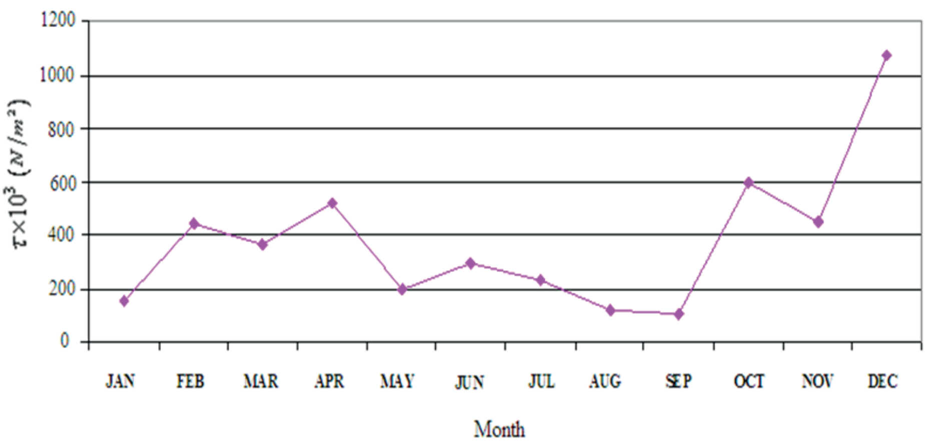

Figure 6. Monthly wind stress in Gorgan Bay in 2008

where, ρ_a is the air density adjacent to the sea level $\left(kg\ m^{-3}\right)$; C_D, the drag coefficient, was calculated with Equation (13) and the fastest wind speed based on the data obtained from the Iran Meteorological Organization for the months of 2008 (Table 3).

Table 3 and Figure 6 show that the wind stress in the Gorgan Bay was the highest in December (1.077 N/m^2), the minimum value was in September (0.104 N/m^2), and the average value of the wind stress in the Gorgan Bay was equal to 0.37 N/m^2.

3.3. Calculation of rainfall *stress* $\left(\tau_r\right)$ *in the Gorgan Bay*

Rain drops in sea surface can cause turbulences. Therefore, in addition to wind stress, we can also consider the rainfall stress of, which is negligible, and can be neglected in relation to wind stress. The following equation has been used to calculate the rainfall stress in the Gorgan Bay (Kara, 1999).

$$\tau_r = R\,U_{10}/3600 \qquad (15)$$

Table 4. Parameters required for calculating rainfall stress in the Gorgan Bay in 2008

Month / Parameters	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
$R\ (^{mm}/_{h})$	0.64	0.12	1.92	2.02	0.64	1.60	2.12	0.25	0.62	0.64	1.77	0.99
$U_{10}(^{m}/_{s})$	9.3	14.8	13.7	16	10.5	12.7	11.5	8.5	8	17	15	21.5
$\tau_r\ (^{N}/_{m^2})$	0.001	0.0004	0.007	0.009	0.002	0.005	0.008	0.0008	0.001	0.003	0.009	0.006

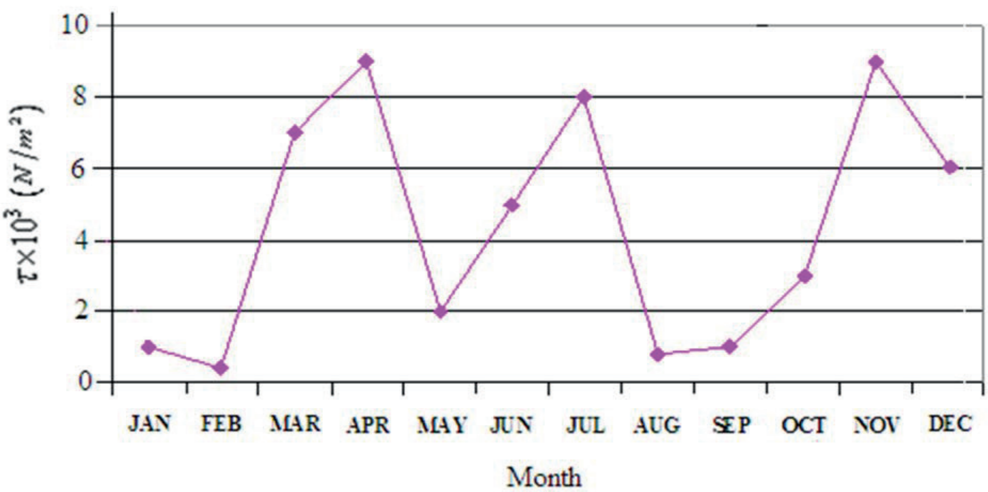

Figure 7. Monthly rainfall stress in Gorgan Bay in 2008

where, R is the amount of rainfall in mm/h, U_{10} is the wind speed at the 10m level in m/s, which according to the Iran Meteorological Organization data is given in Table 4. Table 4 and Figure 7 represent that the rainfall stress in the Gorgan Bay had the maximum values in November and April and its value was lowest in the February, and the average value was 0.004 N/m^2.

Conclusion

1. Drag coefficient is a small dimensionless number that depends on the wind speed and air-sea temperature difference, and it is necessary to be included in the calculation of the heating budget and wind stress. In this study, the annual average of drag coefficient in the Gorgan Bay was set in for 2008.
2. The annual average of wind stress in the Gorgan Bay is 0.37 N/m^2. Wind stress plays an important role in controlling surface water fluctuations and surface temperature variations. Also, the annual average rainfall stress is 0.004 N/m^2, and it can be seen that the rainfall stress can be ignored in comparison with the wind stress in this bay.
3. The Equation (10), presented by the US Navy's Naval Engineering Department in 2006 for calculating the sea level drag

coefficient, is more appropriate for the Gorgan Bay, since the result of this formula is almost the same with the result of one that is determined from the efficiency chart (Table 1).

4. The common result of all the equations used to calculate the drag coefficient of sea level in Gorgan Bay is the fact that the drag coefficient, in the month of December is the highest, and it is the lowest in September.

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