Research Article

The Evaluation of Estoque Model 1990 in Land/Sea Breezes Occurrence over Northern Persian Gulf

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This is a mesoscale modeling study of land/sea breeze in the vicinity of Bushehr, Iran which is on the coast of the Persian Gulf. Two days in September, 2002 are studied using the model presented in Estoque Model (1990) (hereafter referred to as EsM90). The EsM90 produces a realistic day-night wind field somewhat in agreement with observations provided by the Port and Shipping Organization of Iran. The study demonstrates that the model has a 3-hour delay predicting the time of the maximum of sea breeze, but accurately predicts when the end of the sea breeze occurs. Accurate estimates near mountains at the edge of the modeled region require a more complex simulation. The study shows that a reliable modeling of a complicated coastal environment like Bushehr not only depends on land/sea breezes but also on elevations and prevailing winds. This dependence is especially important when local thermal forcings are weak, for example, during late afternoon and at night.

1. Introduction

The Sea Breeze is a common mesoscale phenomenon during the summer months in many coastal areas and has been observed and documented since ancient times [1]. A typical sea breeze may penetrate 50 km or more inland, though its strength depends on the terrain over which it travels. At night the temperature contrast between land and sea reverses and the air over the sea is warmer. This generates a land breeze that blow in the opposite direction to the sea breeze [2]. Sea breeze speed usually ranges between 6 and 10 m/s and from 3 to 5 m/s for a land breeze. The land breezes tend to be weaker than sea breezes. The on/off shore extend of the sea breeze is about 10–20 Km [3].

A typical land/sea breeze circulation is seldom completely free of the effects regarding atmospheric factors and nonatmospheric factors. Of the atmospheric factors, the gradient of the prevailing wind [4–7], the stability [5, 7], the cloudiness and humidity [2, 7], and the season [5], and the nonatmospheric ones, the coriolis force and latitudes [8] and land surface characteristics are most important. Land surface

characteristics may influence the sea breeze circulation in three main ways: the topography [9–15], the vegetation cover, and soil properties such as soil type and soil moisture [9, 16–18], and finally the coastline shape [19, 20]. Among all factors, the prevailing wind is much more important (e.g., [21]). They showed that the characteristics of the sea breeze circulation over southern and east-central Florida are sensitive to synoptic scale wind direction and speed.

On the other hand, a variety of tools, including aircraft measurements [22], pilot balloons (e.g., [23]), satellite images (e.g., [24]) and Doppler radar (e.g., [25]), have been utilized to investigate the thermodynamic and kinematical characteristics and structures of the sea breeze. Laboratory studies (e.g., [26]) and analytical models (e.g., [27]) have contributed extensively to our present knowledge. The sea breeze has also been studied with the help of two-dimensional models (e.g., [4, 28, 29]) and three-dimensional numerical models [21].

As studies developed, it is recognized that meteorological models are essential to understanding pollutant transport, and, therefore, there have been many studies of land/sea

breezes to analysis the dispersion of pollutants (e.g., [30]). Moreover, sea breezes have long been known to modify water motion in coastal regions. In particular, Hyder et al. [31], Chen and Xie [32], O'Brien et al. [33], Craig [34, 35], and Rosenfeld [36] discussed the impact of sea breeze on diurnal currents in shelf seas. So, studying land/sea breezes can help understanding some features at coastal area. To continue this way, we have provided a numerical two-dimensional model to simulate land/sea breeze at a coastal area of the Persian Gulf.

2. Model Description

In this study, we use the Estoque's Model 1990, (EsM90), which had been defined for a complex terrain. In this study we use the model in Estoque [28] (EsM90) which permits specifying a complex terrain. Although, more complex and accurate models have been developed for simulating terrain-induced mesoscale circulations, but as expected, complex models are generally more accurate than the simpler ones, but, the simpler model has the obvious advantage of requiring smaller computers for integrating the model equations. In addition, the EsM90 equations can incorporate the effect of nonuniformities in surface temperature, roughness, and terrain elevation to some extent.

2.1. Model Equations [28]. Primitive model equations use a terrain-following coordinate in the vertical (σ) and the usual coordinates, x and y . The vertical coordinate is defined as

$$\sigma \equiv \frac{z - h}{D - h}. \quad (1)$$

Here, z is the height of a point, h is the height of the terrain, and D is the top of the physical model. The primary equations of the model are the momentum equations, the thermodynamic energy equation, and hydrostatic equation.

$$\begin{aligned} \frac{\partial u}{\partial t} = & -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} + f v - \theta \frac{\partial \phi}{\partial x} - g \frac{\partial h}{\partial x} - K_1 u - K_2(u - u_D) \\ & + \frac{\partial}{\partial x} \left(K_x \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial u}{\partial y} \right) + \left(\frac{\partial u}{\partial t} \right)_s, \\ \frac{\partial v}{\partial t} = & -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - f u - \theta \frac{\partial \phi}{\partial y} - g \frac{\partial h}{\partial y} - K_1 v - K_2(v - v_D) \\ & + \frac{\partial}{\partial x} \left(K_x \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial v}{\partial y} \right) + \left(\frac{\partial v}{\partial t} \right)_s, \\ \frac{\partial \theta}{\partial t} = & -u \frac{\partial \theta}{\partial x} - v \frac{\partial \theta}{\partial y} + \frac{\partial}{\partial x} \left(K_x \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial \theta}{\partial y} \right) \\ & + \left(\frac{\partial \theta}{\partial t} \right)_R + \left(\frac{\partial \theta}{\partial t} \right)_\omega + \left(\frac{\partial \theta}{\partial t} \right)_Q, \end{aligned} \quad (2)$$

where u and v are the components of the velocity along x and y , θ is the potential temperature, f is the coriolis parameter,

and g is gravity. The quantities uD and vD are the wind component at level D . The quantity ϕ is defined as follows:

$$\phi = c_p \left(\frac{P}{P_0} \right)^K, \quad (3)$$

$K = R/c_p$; R = gas constant for air; c_p = specific heat at constant temperature; $P_0 = 1000$ mb. The hydrostatic equation is

$$\frac{\partial \phi}{\partial \sigma} = \frac{-g}{\theta} (D - h). \quad (4)$$

All the above model equations were written in height coordinate.

In the two momentum equations, there are four physical processes which are parameterized, corresponding to the last five terms:

- (a) surface or skin friction: $K_1 u$ and $K_1 v$;
 - (b) momentum exchange between the surface and the upper level, D , $K_2(u - u_D)$ and $K_2(v - v_D)$;
 - (c) horizontal diffusion of momentum,
- $$\frac{\partial}{\partial x} \left(K_x \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial u}{\partial y} \right), \quad \frac{\partial}{\partial x} \left(K_x \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial v}{\partial y} \right); \quad (5)$$
- (d) slope wind generation, $\partial u / \partial t_s$ and $\partial v / \partial t_s$.

The first item above, $K_1 u$ and $K_1 v$, represents the tendency of ground friction to reduce the surface wind speed. The expression for the resistance coefficients, K_1 , is given by

$$K_1 \equiv \frac{C_D |V|}{(D - h)}, \quad \text{where } |V| = (u^2 + v^2)^{1/2}, \quad (6)$$

The drag coefficient, C_D , depends on the thermal stability; the formula for C_D , is presented later in the text. The 2nd item, $K_2(u - u_D)$ and $K_2(v - v_D)$, represents the vertical exchange of momentum between the surface and the layer above. This produces the surface wind maximum during the daytime due to vertical mixing. The expression for K_2 is $K_2 = C_m V_D (1 - \text{Sri}) (1 + C_n h/D)/D$, where C_m , S , and C_n are empirical constants. The value of these constants and other constants are given in Section 2.4. The quantity Ri is Richardson number. Its formula is presented on a later page. At the 3rd item, horizontal diffusion of momentum, the K_x and K_y coefficients which are the eddy diffusion coefficients, vary horizontally according to the formulas,

$$\begin{aligned} K_x = & C_k (\Delta x)^2 \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial x} \right)^2 \right]^{1/2}, \\ K_y = & C_k (\Delta y)^2 \left[\left(\frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 \right]^{1/2}. \end{aligned} \quad (7)$$

These expressions are based on a previous formulation by Smagorinsky et al. [37]. The constant C_k , is an empirical

FIGURE 1: The diurnal wind rose of the synoptic Bushehr station from 1970 to 1995. It is provided from 26-year Bushehr synoptic station data, located at 28°59' E and 50°50' N. It can easily be seen, the predominant wind is NW-SE wind (Shamal), adopted from Iran Meteorological Organization.

TABLE 1: Characteristics of land/sea breezes at different days of September 2002.

Date	Starting time	Ending time	Durations (Hour)	Speed (m/s)	Depth (m)	Horizontal extent (km)
11th	12	22	11	4.8	461	48
12th	11	21	11	4.3	370	43
13th	13	21	09	5.6	627	56
14th	11	21	11	3.9	304	39
16th	11	23	13	3.3	218	33
17th	11	23	13	1.3	192	31
18th	10	23	14	3.5	245	35
Mean	—	—	11.7	3.8	289	38

FIGURE 2: Inputting elevations to the grid points at the model.

quantity, while Δx and Δy are grid distances along the x - and the y -directions. The 4th item, slope wind generation,

represents the physical process which generates upslope motions during the daytime and downslope motions at night. The expression for $\partial u / \partial t)_s$ and $\partial v / \partial t)_s$ is:

$$\left(\frac{\partial u}{\partial t} \right)_s = C_B g \frac{\partial h}{\partial x} \frac{(\theta_s - \theta)}{\theta}, \quad \left(\frac{\partial v}{\partial t} \right)_s = C_B g \frac{\partial h}{\partial y} \frac{(\theta_s - \theta)}{\theta}. \quad (8)$$

Here, C_B , is an empirical constant while θ_s is the temperature of the ground surface.

Additionally, there are also four physical processes in the θ equation:

FIGURE 3: The 3D of terrain which is designed by Surfer 8.

FIGURE 4: The mean 3-hour diagram of the wind speed at September 2002. It shows the actual Bushehr wind conditions for that month. The data adopted from the Synoptic Bushehr Station lactated at 28°59' E and 50°50' N and the Coastal Bushehr Station lactated at 28°54' E and 50°49' N, Iran Meteorological Organization.

FIGURE 5: The mean 3-hour diagram of the temperature at September 2002. This figure shows the actual Bushehr air temperature at that month for starting Initial Conditions. The data adopted from the Synoptic Bushehr Station lactated at 28°59' E and 50°50' N and the Coastal Bushehr Station lactated at 28°54' E and 50°49' N, Iran Meteorological Organization.

(a) horizontal diffusion of heat (the two terms involving K_x and K_y).

(b) radiative temperature changes $(\partial\theta/\partial t)_R$. The expression for this term is based on the concept of Newtonian cooling. Thus, $(\partial\theta/\partial t)_R = C_R[0.9(T_s - T) + 0.1(T_D - T)]$. Here, C_R is an empirical constant while T is temperature at surface anemometer level; T_s is ground surface temperature, and T_D is temperature at $Z = D$.

(c) temperature changes due to vertical motion, $(\partial\theta/\partial t)_W$, for example, cooling due to expansion when the motion is upward; the formula for this term is

$$\left(\frac{\partial\theta}{\partial t}\right)_W = -K_T \frac{\theta_D - \theta}{D - h} (V \cdot \Delta h) + K_C (\theta_D - \theta) \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \quad (9)$$

the first term on the right-hand side represents the effect of orographically forced vertical motion; the second term represents the effect of vertical motions associated with

surface convergence over flat terrain; Here, K_T and K_C are empirical constants;

(d) temperature changes to the sensible heat flux from the earth surface, $(\partial\theta/\partial t)_Q$. In order to estimate this quantity, we assume $\theta(x, y, \sigma, t) = \bar{\theta}(\sigma) + \theta'(x, y, \sigma, t)$, where $\bar{\theta}(\sigma)$ is the vertical variation of the prevailing large-scale potential temperature. Furthermore, we note that, at a particular point (x, y) at any level, σ , $(\partial\theta/\partial t)_{Q,\sigma} = (\partial\theta'/\partial t)_{Q,\sigma}$. We now make the important assumption that the vertical distribution of the heating is approximated by

$$\left(\frac{\partial\theta'}{\partial t}\right)_{Q,\sigma} = \left(\frac{1 - \sigma}{1 - \sigma_a}\right)^n \left(\frac{\partial\theta'}{\partial t}\right)_{Q,a}. \quad (10)$$

Here the subscript, a , refers to values at surface anemometer level; the exponent, n , is an empirical constant. This assumption is based primarily on experience, similar to the power law for wind profiles. From here on, we will drop the subscript, a , from $(\partial\theta'/\partial t)_{Q,\sigma}$ for the sake of simplicity in

FIGURE 6: The mean 3-hour diagram of the pressure at September 2002. It illustrates the actual Bushehr pressure at that month for initial conditions. The data adopted from the Synoptic Bushehr Station lactated at 28°59' E and 50°50' N and the Coastal Bushehr Station located at 28°54' E and 50°49' N, Iran Meteorological Organization.

FIGURE 7: The mean 3-hour diagram of the buoy temperature over the sea surface at September 2002. It shows the Bushehr water temperature at that month. This figure helps us to select the best water temperature for initial conditions. The data adopted from the Synoptic Bushehr Station lactated at 28°59' E and 50°50' N and the Coastal Bushehr Station lactated at 28°54' E and 50°49' N, Iran Meteorological Organization.

notation. Having done that, we will now attempt to express $(\partial\theta'/\partial t)_Q$ in terms of the sensible heat flux, Q , from the earth surface. In order to do this, the first step that is done is to integrate the equation above from the surface to the top of the domain. Thus,

$$\int_0^1 \left(\frac{\partial\theta'}{\partial t} \right)_{Q,\sigma} d\sigma = \left(\frac{\partial\theta'}{\partial t} \right)_Q (1 - \sigma_a)^{-n} \int_0^1 (1 - \sigma)^n d\sigma. \quad (11)$$

Performing the integration and then solving for $(\partial\theta'/\partial t)_Q$, one gets

$$\left(\frac{\partial\theta'}{\partial t} \right)_Q = (1 - \sigma_a)^n (n + 1) \int_0^1 \left(\frac{\partial\theta'}{\partial t} \right)_{Q,\sigma} d\sigma. \quad (12)$$

Note, however, that the integrand represents the total heating of air column due to sensible heat flux. Therefore, $\int (\partial\theta'/\partial t)_{Q,\sigma} d\sigma = (Q/(D - h))$.

Combining this equation with the preceding one, one gets

$$\left(\frac{\partial\theta'}{\partial t} \right)_Q = \frac{(n + 1)(1 - \sigma_a)}{D - h} Q \approx \frac{n + 1}{D - h} Q = \left(\frac{\partial\theta}{\partial t} \right)_Q. \quad (13)$$

Finally, the heat flux (Q) must be expressed in terms of u , v , σ , and the surface temperature, θ_s . On the basis of the so-called bulk aerodynamic method, the formula is: $Q =$

$C_D(u^2 + v^2)^{1/2}(\theta_s - \theta)$. The drag coefficient (C_D) is, in turn, formulated in terms of Richardson number (Ri) and the roughness parameter (Z_0), following a suggestion by Louis et al. [38]. The formula is

$$C_D = \begin{cases} \frac{C_{DN}}{[1 + 15Ri(1 + 5Ri)^{1/2}]}, & Ri > 0, \\ C_{DN} \left\{ \frac{1 - 15Ri}{[1 + 75C_{DN}(-RiZ_a/Z_0)^{1/2}]} \right\}, & Ri \leq 0, \end{cases}$$

$$C_{DN} = \left[\frac{k_0}{\ln(Z_a/Z_0)} \right]^2, Ri \equiv \frac{Z_a g(\theta/\theta_s - 1)}{(u^2 + v^2)}. \quad (14)$$

Here, k_0 is the Karman constant, Z_a is the height of the surface observations for wind and temperature. The quantity, C_{DN} , is the customary value of the drag coefficient for neutral stratification.

The last important aspect of the model formulation which will be discussed is determination of the geopotential of the surface anemometer level, ϕ_a . This is done by integrating the hydrostatic equation from the top of the model domain (σ_D) to the surface anemometer level (σ_a). In connection with the integration, one has to specify the vertical distribution of θ' . For this purpose, we make the same power law assumption which was made previously. Thus, $\theta'_\sigma = \theta'_a[(1 - \sigma)/(1 - \sigma_s)]^n$. Again, we will drop the subscript, a , in θ_a (for simplicity of notation) with the understanding that θ refers to the surface anemometer level. We note further that: $\theta_\sigma = \theta'_\sigma + \bar{\theta}(\sigma)$ with θ'_σ given by the preceding formula. Substituting this in the hydrostatic equation, (4), and integrating, we get: $\phi \equiv \phi_a = \phi_D + g(D - h)[\alpha - (\beta\theta')/(1 - \sigma_a)^n]$; $\alpha \equiv \int_{\sigma_a}^1 (1/\theta(\sigma))d\sigma$, and $\beta \equiv \int_{\sigma_a}^1 (1 - \sigma)^n/[\theta(\sigma)]^2 d\sigma$.

We have now finished the formulation of the model. All these information about EsM90 equations, the relationships between quantities and parameters are derived from Estoque [28].

2.2. Model Spatial and Temporal Situation. We choose Bushehr, Iran and its surrounding area (Figure 9) because of

FIGURE 8: Model algorithm.

TABLE 2: Characteristics of land/sea breezes at different days of October 2002.

Date	Starting time	Ending time	Durations (Hour)	Speed (m/s)	Depth (m)	Horizontal extent (km)
2nd	13	21	09	3.3	218	33
3rd	11	21	11	3.6	260	36
8th	11	21	11	3.1	192	31
12th	12	21	10	3.7	274	37
28th	11	19	09	2.2	097	22
Mean	—	—	10	3.2	205	32

TABLE 3: Characteristics of land/sea breezes at different days of November 2002.

Date	Starting time	Ending time	Durations (Hour)	Speed (m/s)	Depth (m)	Horizontal extent (km)
4th	12	21	10	6.6	871	66
10th	12	22	11	4.3	370	43
16th	13	20	08	5.9	696	59
17th	14	18	05	3.9	304	39
20th	15	19	05	4.4	387	44
Mean	—	—	7.8	5.0	500	50

TABLE 4: Characteristics of land/sea breezes at different days of December 2002.

Date	Starting time	Ending time	Durations (Hour)	Speed (m/s)	Depth (m)	Horizontal extent (km)
19th	12	21	10	4.4	387	44
20th	13	20	08	1.8	65	18
25th	11	23	13	4.9	480	49
27th	16	19	04	6.2	769	62
28th	13	22	10	5.1	520	51
Mean	—	—	09	4.5	405	45

FIGURE 9: The simulation of wind velocity at 0900 LT on 23 September 2002.

FIGURE 10: The simulation of wind velocity at 1200 LT on 23 September 2002.

its particular coastal line, its two climatological stations, and its important nuclear power plant. The diurnal variations of wind characteristics in this area, especially near the coastal zone, are normally attributed to the land and sea breeze effects [39]. The topographic map was obtained from The Geographical Armed Force Organization of Iran. It is based on UTM. system by the scale of 1:500,000 at the WM, VM, WN, and VN sections of this system, between $28^{\circ}15' - 29^{\circ}15' \text{ E}$ and $50^{\circ}16' - 51^{\circ}15' \text{ N}$. The Bushehr basin is an almost flat region but has a mountain range, the Mond

Mountains, whose direction is southeast-northwest, (SE-NW). Consequently, this area may be significantly affected by up- and downslope winds. These up- and downslope winds are valley and mountain breezes, respectively.

Considering Bushehr Climate was the next step. This region has a warm, humid climate, which is affected by the Mediterranean cyclones and the Sudanese lows in the winter, and summer lows in the summer. Wind rose (Figure 1), which is provided from the Bushehr synoptic station, located at $28^{\circ}59' \text{ N}$ and $50^{\circ}50' \text{ E}$, shows that the predominant wind

FIGURE 11: The simulation of wind velocity at 1500 LT on 23 September 2002.

FIGURE 13: The simulation of wind velocity at 2100 LT on 23 September 2002.

FIGURE 12: The simulation of wind velocity at 1800 LT on 23 September 2002.

FIGURE 14: The simulation of wind velocity at 0000 LT on 24 September 2002.

is Northwesterly (Shamal wind). Since the prevailing wind can mask the land/sea breeze, the monthly data are required. Observational studies of land/sea breeze, which were provided by The Port and Shipping Organization of Iran, for some selected days of September, October, November, and December (2002) have been shown in Tables 1, 2, 3, and 4, respectively. The tables illustrate that September has the most mean land/sea breezes. Due to this reason, September was selected as an optimum month for modeling. According

to meteorological data, 23 September 2002 was the best, because there was no prevailing wind before and after that day.

Then, a rectangular grid with a horizontal 2.5 km grid spacing was used. The vertical domain was 2 km, since breeze could not go higher. (A typical sea breeze has a height of about 1 km. [2]).

The evaluations, h , were determined as follows: suppose point, A, if it was on a contour line, its evaluation was

FIGURE 15: The simulation of wind velocity at 0300 LT on 24 September 2002.

FIGURE 17: The simulation of wind velocity at 0900 LT on 24 September 2002.

FIGURE 16: The simulation of wind velocity at 0600 LT on 24 September 2002.

FIGURE 18: The simulation of wind velocity at 1200 LT on 24 September 2002.

that height of contour line (Figure 2). Otherwise, it was determined by linear interpolation between the nearest contour lines as in the following equation:

$$h_A = 1000 \times \frac{AM}{MN} + 1200 \times \frac{AN}{MN}. \quad (15)$$

The resulting topography is illustrated in Figure 3.

2.3. Initial and Boundary Conditions. Solving the EsM90 model requires specification of the initial conditions. We set

$u(x, y)$, $v(x, y)$, $\theta(x, y)$, and $P(x, y)$ to be the value of u , v , θ and P at the surface anemometer level at initial time, $t = 0$.

These variables are specified from observations, and so that the initial flow is geostrophically balanced. However, values corresponding to the prevailing flow at the surface anemometer were sometimes chosen. Figures 4 and 5 show the 3-hour wind magnitudes and temperature on September 23, 2002 at Bushehr and its coastal station. As can be seen,

FIGURE 19: The simulation of wind velocity at 1500 LT on 24 September 2002.

FIGURE 21: The simulation of wind velocity at 2100 LT on 24 September 2002.

FIGURE 20: The simulation of wind velocity at 1800 LT on 24 September 2002.

FIGURE 22: The simulation of wind velocity at 0000 LT on 25 September 2002.

for example, $|\vec{U}| = 0.7 \text{ m/s}$, $\theta = 27.4^\circ$ (Bushehr) and $|\vec{U}| = 2.2 \text{ m/s}$, $\theta = 28.6^\circ$ (Bushehr coastal station) at 0600 Local Time (LT). In addition, model requires the vertical values of θ corresponding to the large-scale flow; that is: $\theta(z) = \bar{\theta}(z)$; $h \leq z \leq D$ or $\theta(\sigma) = \bar{\theta}(\sigma)$; $0 \leq \sigma \leq 1$. On the basis of Figure 5, $\theta(x, y) = 26^\circ\text{C} = 299 \text{ K}$, and, on the basis of Figure 6, $P(x, y) = 1003 \text{ Pa}$. while the land surface temperature varies with time in this study, the water temperature is held fixed at 33°C because there is only a

little diurnal variability (Figure 7). The 48-hour simulation starts at 0600 LT, 23 September 2002 and ends at 0600 LT on 25 September. The initial large-scale flow is assumed approximately zero ($u(x, y) = v(x, y) = 0.1 \text{ m/s}$). Recalling that Figure 4 indicates $|\vec{U}| = 0.7$ and 2.2 m/s at 6:00 LT.

Reflective boundaries were applied at open boundaries. Thus for a general quantity, S , we have $S_n = S_{n-1}$, where S_n is the open boundary value and S_{n-1} is its adjacent value at the model domain. On the coastal boundaries, rigid-lid

FIGURE 23: The simulation of wind velocity at 0300 LT on 25 September 2002.

FIGURE 24: The simulation of wind velocity at 0600 LT on 25 September 2002.

conditions were applied, that is: $S_n = 0$. At inflow point, values were held fixed. At outflow point, the values are being predicted by the model.

The roughness parameter, $Z_0(x, y)$, is taken as 0.1 m for land and 1×10^4 m for water. Surface temperature, $\theta_s(x, y, t)$, is taken as $26^\circ\text{C} = 299\text{ K}$ (due to Figure 5) for $t = 0$, and for $t > 0$, it is being predicted by the formula.

2.4. EsM90's Scheme and Constants. We use the same differencing methods which are described at EsM90. Thus, the

forward upstream difference technique of EsM90 is used here.

The time step used here is 300 seconds and the 3-hour outputs were printed and analyzed.

The initial values of u , v , and θ were specified so as to be in geostrophic balance. Other parameters and model constants which were used, are $C_m = 6 \times 10^{-2}$; $S = 0.5$; $C_n = 35$; $C_k = 1 \times 10^{-4}$; $C_B = 0.0$; $C_R = 3 \times 10^{-5}$; $K_T = 1.0$; $K_C = 0.05$; $n = 0.01$; $Z_a = 10\text{ m}$.

The model constant values are determined by numerical experiments in which the model equations were solved by using different values of a particular constant. Then, the particular constant values which gave the most realistic result were selected. The chosen values may not be the optimum ones to be used universally.

2.5. EsM90's Algorithm and the Procedures of the Calculations. The numerical integrations are done by the following step-by-step procedure (See Figure 8 for more details).

- Using the specified values of θ and $\bar{\theta}$ at the surface anemometer level, compute the corresponding value of θ' .
- Compute the heat term, Q .
- Using the value of θ' , compute ϕ .
- Compute the local tendency terms, $\partial u/\partial t$ and $\partial v/\partial t$.
- Using the computed values of $\partial u/\partial t$ and $\partial v/\partial t$, calculate new (forecast) values of u and v .
- Compute the temperature tendency, $\partial \theta/\partial t$.
- Using this value of $\partial \theta/\partial t$, calculate new (forecast) values of θ .
- Using the forecast values of u , v and θ obtained in steps (e) and (g), repeat steps (a) to (g).

Continue this repetitive procedure until the sum of the Δt 's is equal to the desired range of the forecast.

The EsM90 program was run on the domain, centered at Bushehr peninsula by a personal computer with Pentium (R)-4, CPU = 1.70 GHz, and RAM = 1 Giga Byte for 48 hours; then, eventually its result was illustrated by Surfer 8 software. The method which was used to make grid files was Kriging.

3. Results and Discussion

This study has attempted to produce the land/sea breeze development over the Bushehr peninsula. This peninsula is fairly complicated in that there is a large embayment to the north and coastal mountain to the south. Although this mountain is not very high (less than 400 m), the production of up-and downslope winds cannot be ignored. Figures 6–21 illustrate the model's wind vectors at the anemometer level. The tick lines in these figures are the coastlines and thin ones are terrain height (contouring interval 100 m). A velocity scale (in m/s), for each figure is provided. The two large solid circles locate the meteorological stations at Bushehr (24° N , 29° E) (denoted as Bush) and at the near Bushehr (22° N , 28° E) (denoted as Bushcoast). The large $\times$ demonstrates the

FIGURE 25: Maximum of wind velocity which is predicted for 0600 LT on 23 September 2002 to 0600 LT on 25 September 2002.

FIGURE 26: The wind velocity at point Buoy (22, 24) for two study day.

location of the meteorological buoy station. The open stars locate three landmarks: Burnt Castle, Bulkhayre Ameri, and Salem Abad. The solid triangle denotes the peak of the Mond Mountains. The capital A is an authority point, (38, 11), on the eastern side of the Mond Mountains. This place is adopted to study the model ability to mix land/sea breezes and mountain/valley breezes.

3.1. Start Time and Duration of Breezes. The sea breeze starts at 0900 LT along coastal line (Figure 9) and as sea breeze penetrates into land at 1200 and 1500 LT, upslope winds are also generated (Figures 10 and 11). By looking at Figure 12, we see that wind field is being reduced and at 2100 LT the surface wind is perfectly calm. The observations of the Port and Shipping Organization of Iran, (Table 1), show that $2100 \text{ LT} \pm 0100$ is when the land/sea breezes end. So our study using the EsM90 model realistically predicts when the land/sea breezes end. At 0000 LT downslope winds start at Mond Mountain. Land breezes develop at 0300 LT (Figures 15 or 23) and 0600 LT (Figures 16 or 24) over the Persian Gulf and end at 0900 LT (Figure 17). Observational data shows that land breeze ends exactly at 0600 LT (Figure 4), while, this time land breeze model's prediction exists and finishes at 0900 LT.

By comparing the two days, it seems the sea breeze extends in to the afternoon. The duration of the sea breeze on the first and second day is about 15 h and 12 h, respectively, (Figure 25), while the observed duration is about 15 h (Figure 4). But in both days the sea breeze is finished at 2100 LT (Figure 26). The duration and end time are two important results of this simulation; observational studies similarly indicate it is about 11 to 13 hours at September (Table 1). Parvaresh et al. [39] showed during the 21-day period (15 July–4 August 2000), that sea breezes have finished at 2100 LT. Their data were recorded at the same buoy station indicated by $\times$ in our simulation figures [39]. The prediction duration of the land breeze is 9 h; however the

observations of Bushehr Synoptic Station show no land breeze and Bushehr Coastal Station's land breeze's duration is just about 6 h. Thus the model's predictions overpredict the duration of land breeze by about 3 h.

3.2. Intensity and Horizontal Extension. After starting model and by approaching noon, intensity increases so that it reaches a maximum of 9.3 m/s at 1200 LT on the 1st day (Figure 10) or 7.3 m/s at 1500 LT on the 2nd day (Figure 19). Then, it decreases by the evening and disappeared at 2100 LT in both days (just small values at the back of the mountain). If we make 1800 LT an exception, it can be said that sea breeze velocity on the 1st day is stronger than the 2nd one, while land breeze is reversed. Maximum of land breeze speed is 5.2 m/s at 0000 LT, 5.7 m/s at 0300 LT, and 8.5 m/s at 0600 LT, all of them take place on the 2nd day. When the land breeze ends at 0900 LT, just a weak sea breeze with the maximum of 2.2 m/s is predicted.

The predicted sea breeze at Bushehr meteorological station is less than the observed wind speed by 1 m/s on the average; the predicted land breeze is somewhat greater than the observation (Figures 4 and 27). The maximum predicted sea breeze occurs at 1200 LT while the observed one is three hours later at 1500 LT (Figures 4 and 27), but at the 2nd day is exactly the same.

Parvaresh et al. [39] showed that wind speed at 10 m above sea level (U_{10}) varied between 0.34 and 10.38 m/s with a characteristic diurnal oscillation. They also resolved wind speed into two components, along and across the shore. Their results show that the wind speed associated with the land breeze is less than 6 m/s, but that of the sea/land breeze is greater [39]. Although the model simulates a different month and year than when the data were collected, and the observations (as noted in [39]) do not remove the prevailing wind effect from the reported land/sea breeze, the model results show the land breeze $< 6 \text{ m/s}$ at the observations, which is in agreement with the observations.

FIGURE 27: The predicted wind velocity at point Bush (24, 29) for two study day.

FIGURE 28: The predicted wind velocity at point Bushcoast (22, 28) for two study days.

FIGURE 29: The predicted wind velocity at an authority point A (38, 11) for two study day.

If we use Bush pint (24° N, 29° E or (24, 29)) as a reference, by 1200 LT on 23 September 2002 (Figure 10), horizontal extension of sea breeze is about 20 km and doubled by 1500 LT. By 1500 LT on 24 September 2002 (Figure 19), it is about 20 km in land, whereas land breeze is at about 60 km at 0600 LT over the sea. Comparing these two days, 2nd day's sea breeze shows a shorter horizontal penetration than the 1st one at the same times, while land breeze is opposite.

Since, sea breeze start at $u = v = 0.1$ m/s on the first day, these values are different on the next day, sea breeze, therefore, starts from the previous land breeze, and this delay to reproducing land/sea breezes influence, both the intensity and horizontal extension, to some extent.

3.3. The Effect of Coastal Topography. At 1200 LT and 1500 LT (Figures 13 and 14), a convergence area can be seen over the Bushehr peninsula, and also near Burnt Castle, Bulkhayre Ameri and Salem Abad. Lyons et al. [40] and Nicholls et al. [41] have shown that thunderstorms frequently form near and ahead of sea breeze fronts; so cumulus clouds and thunderstorms are probable at the convergence zones. Convergence zones are not restricted to sea breezes. Two of them are generated at 0300 and 0600 LT over the Persian Gulf when land breezes developed perfectly over the sea.

If we look carefully to the model prediction of breezes at 2100 LT, it can be recognized that the maximum velocity values (2.6 m/s on 23 September 2002 and 3.2 m/s on 24

September 2002) is returning to the values back of the mountain.

One gets the impression from the model results (Figures 9–24) that the land/sea breeze is less pronounced along the coast at the northern boundary, and that this breeze is quite pronounced along the southern coast in the region near Mond Mountain. The predicted winds at point A on the lee side of mount (Figure 29) show that the land/sea breeze is generally stronger there than at the Bushehr and Bushehr Coastal stations (Figures 27 and 28).

4. Conclusion

In brief, the EsM90 on Bushehr has some defects to reduce enough as breeze goes far in land or sea. Furthermore, some deviations occur on the prediction of breeze duration, although it is much more powerful to bring a good simulation based on coastal shape and approximately real values (about 0–3 m/s difference). The model also combines land/sea breezes by mountain/valley breezes very well at the side near the coast but be defeated to produce separately mountain/valley breezes as can be seen at the back of Mond Mountain.

The duration of the sea breeze on the first and second day is about 15 and 12 hours, respectively. The model predicts well the land breeze at the Bushehr coastal station.

The land/sea breeze is less pronounced along the coast at the northern boundary, and that this breeze is quite

pronounced along the southern coast in the region near Mond Mountain.

In the end, a satisfied wind field is produced which can show up- and downslope winds in addition to land/sea breezes.

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