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Performance evaluation of parametric models in the hindcasting of wave parameters along the south coast of Black Sea

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In the present study, the performances of four parametric models in the wave hindcast were evaluated by comparing with wave measurements at two locations on the Black Sea. Wilson, SPM, JONSWAP, and CEM methods were used to hindcast significant wave height (H_s) and mean wave period (T_z). Wind data required to perform wind-wave hindcasts is gathered by the Turkish State Meteorological Service (TSMS) and the European Centre for Medium-Range Weather Forecast (ECMWF). Wave data set measured at deep water location for Hopa and Sinop buoy stations within the NATO TU-WAVES project was used to validate wind-wave hindcasts. A set of new formulations for wind-wave hindcast was proposed for the Black Sea. Sensitivity analyses were performed for both parametric methods and newly proposed equations. Finally, it is concluded that the CEM method compared to other methods generally produces more accurate results for the hindcasts of wave parameters in both stations. It is observed that parametric methods do not have the sufficiently accurate results in the Black Sea. Proposed formulations cannot produce results at desired level to represent all southern coasts of the Black Sea in comparison to existing parametric methods.

[**Keywords:** Wave hindcasting, Significant wave height, Wave period, Wave statistics, Parametric methods, Black Sea]

Introduction

Wind waves play a significant role in a variety of ocean and coastal activities including design of coastal structures, sediment transport, coastal erosion, and pollution transport[1]. They attack shore protection structures, reshape beaches, affect marine structures, and are hence important for commercial, military, and recreational activities[2].. Numerical models solve the energy balance equation throughout grid points over the water, where active wave generation is taking place. These models require abundant bathymetric, meteorological, and oceanographic data. In some regions, these data are not available and numerical modelling is both difficult and expensive[3]. Moreover, for first estimates in many cases, the use of these models is not economically justified[4,5].

Several empirical methods such as PM (Pierson and Moskowitz[6]), Wilson (Wilson[7]), SMB (Bretschneider[8]), JONSWAP (Hasselmann et al[9]), Donelan (Donelan[10]), SPM (US Army[11]), and CEM (US Army[12]) have been developed and proposed for the different seas in the wave hindcast or forecasting. These methods have been often used for various engineering purposes especially in Turkey and, until today, their performances have been evaluated by some researchers[13]. Bishop[14] researched performances of three manual wave hindcast models at two deep-water locations in Lake Ontario. He examined only fetch-limited, pseudo-steady-state events and found that the accuracy of the Donelan model was slightly superior to that of the SMB and JONSWAP methods. Bishop *et al*[15] compared with measured wave data and with four wave prediction formulas including SPM, SMB, JONSWAP, and Donelan methods. Their results indicated that SPM model tends to overpredict wave height and period and, statistically, is the poorest predictor of the four methods tested. Kazeminezhad *et al*[13] also examined the accurate of the CEM method in Lake Ontario for fetch limited condition while Moeini and Etemad-Shahidi[16] studied performance of the SPM method in Lake Erie. They concluded that the SPM and CEM methods over-predicted significant wave height while SPM method under-estimated peak spectral period. Etemad-Shahidi *et al*[5] investigated performances of three parametric methods (CEM, SMB, and Wilson models) for predicting the wave height in Ontario and Erie lakes. They found that the parametric methods were more accurate in the fetch limited condition than in the duration limited condition. The comparison of their models also showed that the accuracy of the SMB method was very close to that of the Wilson method while the SMB method was far more accurate than the CEM method. As can be seen from the literature, different methods or formulas have been available in different seas or lakes.

The aim of the study is to evaluate the capabilities of four different parametric wave models, which have been proposed in different coastal and maritime standards, to reproduce the wave data collected by wave buoys at two positions along the southern coast of the Black Sea. For this purpose, Wilson, JONSWAP, SPM, and CEM methods were applied to predict wave parameters. In the application of these methods, some sensitivity analyses were performed and accuracy of the developed models was determined and discussed by using buoy measurements at Hopa and Sinop stations in the Black Sea. Finally, development of an appropriate parametric method for the Black Sea was tried and for this process some scenarios were investigated. The proposed model decreased scatter index, but the correlation coefficient was not enhanced.

Materials and Methods

Study area and the used data

In this study, wave hindcasts were performed for two wave measurement stations (Hopa and Sinop buoys) in the Black Sea. The Black Sea has a laterally-prolonged scale of about 1175 km in the east-west direction between 28° E and 41.5° E. Its width is about 600 km in the north-south direction between 41°N and 46°N. This inland sea has an area of 436400 kilometer squares (not including the Sea of Azov), a maximum depth of about 2588 m, and a volume of 547000 km^3 [17] Fig. 1 shows the map of the study area and the locations of the buoy (wave measurement station) and meteorological stations.

Fig. 1 Location of Study Areas

Table 1–The characteristics of the buoy and meteorological stations

Station	Latitude	Longitude
Sinop TSMS station	42° 01' 60" N	35° 09' 60" E
Hopa TSMS station	41° 24' 24" N	41° 25' 58" E
Sinop buoy station and Sinop ECMWF grid point	42° 07' 24" N	35° 05' 12" E
Hopa buoy station and Hopa ECMWF grid point	41° 25' 24" N	41° 23' 00" E

The wind data required to perform wind-wave hindcasts in this study was obtained from Turkish State Meteorological Services (TSMS) and European Centre for Medium-Range Weather Forecast (ECMWF). Two coastal wind measurement stations operated by TSMS which are the closest stations to Hopa and Sinop buoys were selected as a wind data source. Average of the recorded wind data of the closest four ECMWF grid points to Hopa and Sinop buoys was used for wave hindcasting. The characteristics of the buoy and the wind recording stations are given in Table 1. Both wind data sources have advantages and disadvantages. While the TSMS data have 1 hour time resolution, the ECMWF wind fields have a resolution of 6 hours. In other words, while there are 24 pieces of data in 1 day record of the TSMS, the data set of the ECMWF has 4 data in a day. However, TSMS data base does not have the spatial resolution. It provides temporal data at several points along the southern coastline of the Black Sea. On the other hand, the ECMWF data set has spatial resolution of 0.25° and 0.25° in both latitude and longitude. The used wind data consist of hourly measured wind speed and direction for the TSMS, while they are *u* and *v* wind components for the ECMWF. Joint probability distributions of wind speed and direction for four wind recording stations (for two different wind sources at two locations) are given in Figs. 2 and 3.

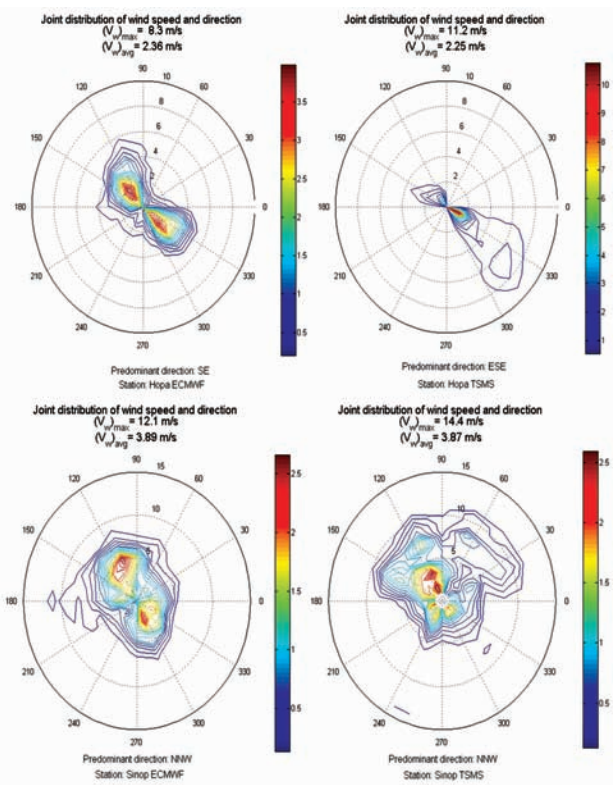


Fig. 2—Spatial variability in DOC and fluorescence indices in the Sundarban mangroves.

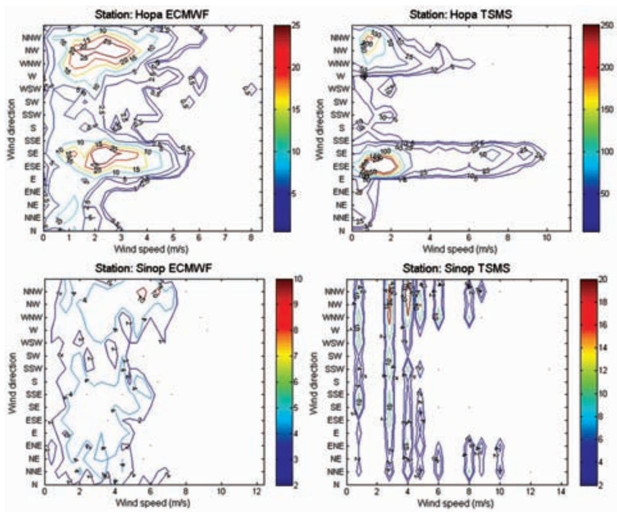


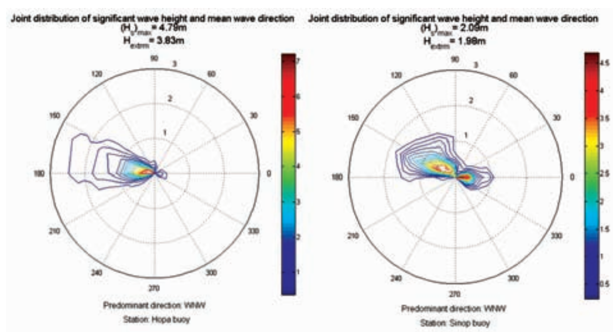
Fig. 3—Spectral characteristics of four fluorophore components identified by the PARAFAC modeling.

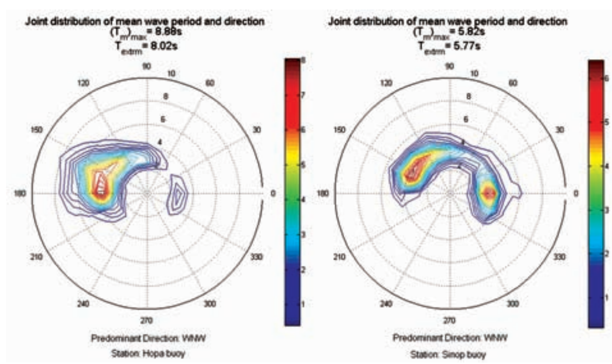
The buoy wave data (significant wave height and mean wave period) collected in Hopa and Sinop locations within the NATO TU-WAVES project which was carried out with financial support provided by the Science for Stability Programme (Phase III) of NATO was used to validate the wave hindcasts. While the period of the used wind and wave data collected for Sinop buoy and meteorological stations includes 1994 (November and December months), 1995 (November and December months), and 1996 (from January to June) years, the record period for Hopa stations includes whole year of 1995. Water depths in the buoys are about 100 m and the Hopa buoy is deployed 4600 m far away from the coast while the Sinop buoy was approximately 11600 m off-shore. Statistical summaries of wave and wind data for all stations are presented in Table 2. This table shows that the observed waves at both buoy stations were

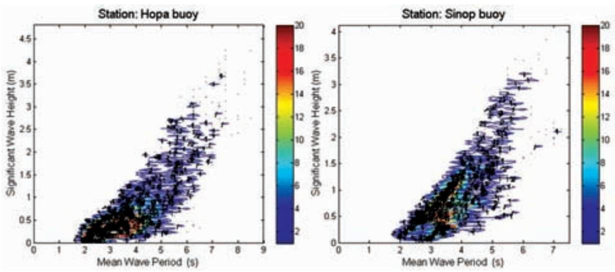
Table 2–Statistics of the recorded wind and wave data during the time period in buoys, ECMWF grid points, and TSMS stations considered in this study

Station	Number of data	Parameter	Maximum	Minimum	Average
Sinop buoy	1010	Mean wave direction (derece)	359.957	0.000	204.300
	5156	Significant wave height (m)	4.786	0.034	0.601
		Mean wave period (s)	8.885	1.889	3.784
Hopa buoy	3552	Mean wave direction (derece)	360.000	0.000	267.842
		Significant wave height (m)	4.342	0.068	0.917
		Mean wave period (s)	7.404	1.940	3.957
Sinop ECMWF grid	1218	Wind speed (m/s)	12.142	0.230	4.075
point		Wind direction (derece)	359.714	0.581	198.962
Sinop TSMS station	1467	Wind speed (m/s)	15.400	1.000	3.944
		Wind direction (derece)	360.000	22.500	222.715
Hopa ECMWF grid point	1462	Wind speed (m/s)	8.306	0.050	2.355
		Wind direction (derece)	359.907	1.042	208.614
Hopa TSMS station	8562	Wind speed (m/s)	11.200	0.000	2.196
		Wind direction (derece)	360.000	22.500	186.727

deep water waves because maximum measured peak periods at the Hopa and Sinop buoys were 7.404 s and 8.885 s, and thus, the minimum ratio of the water depth to the wave length at both stations were 1.17 and 0.81, respectively. Moreover, it is understood that the average wind and wave directions for Sinop buoy are from the north northwest (NNW) and west northwest (WNW) directions, respectively. Besides, it is seen that waves at Hopa buoy often track from the west northwest (WNW) direction while winds blow mostly from the southeast (SE) and east southeast (ESE) direction. Joint probabilities (significant wave height & mean wave direction, mean wave period & mean wave direction, significant wave height & mean wave period) of both buoy locations are shown in Figures 4, 5, and 6, respectively. These joint probabilities plots for Hopa station represent the data of whole months of 1995 but they correspond from the data of first six months of 1996 and last two months of 1994 in Sinop station. Therefore, while







the joint probability plots for Hopa station represent the characteristics of its wind and wave climate they can not probably symbolize fully the characteristics of wind and wave climate of Sinop buoy station.

Hindcasting of wind generated waves

Since the measurement of wind waves is difficult and expensive, most of the time available observations are very short. Along the Turkish coasts, instrumental recording of wave data is not yet systematically carried out. There exist only a few wave measurements activities in recent years which are related to some projects. Wave parameters within the NATO TU-WAVES project which is sponsored by science for peace unit of NATO were recorded at few locations. These measurements are insufficient to be taken into account in the planning phase of a project. Therefore, wave parameters required in planning are estimated from long term wind records[18].

Often wind records taken from observations (ships, coastal, offshore structures, buoys, etc.) do not coincide with the standard 10 m reference level. They must be converted to the 10 m reference level to predict the waves. An equation is given to adjust wind speed measured at elevation z to a 10 m height that is appropriate for use in wave hindcast equations. The elevation adjustment equation is given as [12]:

If the data is measured over land it is required that the wind speed (U_{land}) at 10-m elevation over land must be converted into the wind speed (U_{water}) at 10 m elevation over water. For this purpose, a formula given by Hsu [19] is used as:

$$U_{10} = U_z \left(\frac{10}{z} \right)^{1/7} \quad ...(1)$$

$$U_{water} = 3.0 \left(U_{land} \right)^{0.67} \quad ...(2)$$

Many coastal engineering studies use wave information based on the following assumptions: steady wind speed, steady wind direction (thus, constant fetch), and duration of wind long enough to provide fetch-limited, as opposed to duration-limited, waves[14.] So, in the hindcast of wave parameters, the required variables can be determined as wind speed, fetch length, and wind duration[20].

Fetch length

Wind fetch length was defined as the unobstructed distance that wind can travel over water in a constant direction. In the areas having the coastal irregularities such as inlet, gulf, and embayment, different methods were described in the literature to take into account the effect of the neighboring coasts to fetch length. The most frequently used method is the effective fetch. The concept of effective fetch assumes that: waves are generated over a 45° range either side of the wind direction and energy transfer from wind to waves is proportional to the cosine of the angle between the wind and wave directions, and wave growth is proportional to fetch length. Hence,

$$F_{eff} = \frac{\sum F_i \, \mathrm{Cos}^2 \, \alpha_i}{\sum \mathrm{Cos} \, \alpha_i} \quad (3)$$

where F_{eff} is the effective fetch and is the length to be used in the all parametric methods. F_i and Li_i are fetch lengths and angles measured at 7.5° interval [21, 22].

Wind duration

To determine the duration of winds, definition of constant wind was used[12]. In this way, wind duration at i^{th} hourly data point was considered to be equal to number of preceding consecutive and acceptable hours which satisfies following:

$$\left| U_i - \overline{U} \right| < 2.5 \text{ m/s} \quad ...(4)$$

$$\left|D_i - \overline{D}\right| < 15^{o} \qquad ...(5)$$

where $\overline{U}$ and $\overline{D}$ are the average of preceding consecutive and acceptable hourly wind speed and direction, respectively. U_i and D_i are the wind speed and direction at i^{th} hourly data point[13].

Parametric wave hindcast methods

The SPM Method

In this method, significant wave height (H_s) and peak period (T_p) which is the period at the peak of the wave energy density spectrum are associated with the wind speed, duration, and fetch length.

$$\left(H_s, T_p\right) = f\left(U_A, F, t\right) \qquad ... (6)$$

where U_A is the wind stress factor (*m/s*) which is defined as:

$$U_A = 0.71\, U_{10}^{1.23} \qquad ... (7)$$

In the fetch limited case, for the hindcast of waves from wind, SPM method [11] suggested a parametric model expressed as:

$$\frac{g\,H_s}{U_A^2} = 0.0016\left(\frac{g\,F}{U_A^2}\right)^{0.5} \qquad ... (8)$$

$$\frac{g\,T_p}{U_A} = 0.286\left(\frac{g\,F}{U_A^2}\right)^{1/3} \qquad ... (9)$$

$$\frac{g\,t_{min}}{U_A} = 68.80\left(\frac{g\,F}{U_A^2}\right)^{2/3} \qquad ... (10)$$

where t_{min} is minimum wind duration (s) and F is fetch length (m) which was computed as the effective fetch length in this study. If the wind duration is shorter than the minimum necessary duration to obtain fully developed waves for a certain fetch, the duration limited case is valid. US Army[11] suggests to make use of the formulae for the fetch limited case. It proceeds as: replace t_{min} by t in Equation 10 and calculate the equivalent fetch length. Then, calculate H_s and T_p from Equations 8 and 9 where fetch is the equivalent fetch length[23,24] . The relationship between peak period and mean wave period which is the only spectral period that has an equal in the time domain mean period T_z, in the narrow band approximation equal to T_{m02}, is expressed in the following equation for peak enhancement factor (γ) = 3.3[21]

$$T_z \cong 0.7775\, T_p \qquad ... (11)$$

The Wilson Method

In this method, the minimum duration for the full growth at a given fetch length is approximately calculated by[7]:

$$t_{min} = 1.0\, F^{0.73}\, U_{10}^{-0.46} \qquad ...(12)$$

where U is the wind speed at 10 m above the sea surface (*m/s*), t_{min} is in *h*, and F is in *km* which was computed as the effective fetch length in this study. In the fetch limited condition, the significant wave height (H_s) and period (T_s) are expressed as:

$$T_s = 8.61\frac{U_{10}}{g}\left[1-\left[1+0.008\left(\frac{g\,F}{U_{10}^2}\right)^{1/3}\right]^{-5}\right] \qquad (13)$$

$$H_s = 0.30\frac{U_{10}^2}{g}\left[1-\left[1+0.004\left(\frac{g\,F}{U_{10}^2}\right)^{0.5}\right]^{-2}\right] \qquad (14)$$

If the wind blowing duration is less than t_{min}, the assumptions for fetch limited condition become in valid. For this case, equivalent fetch which differs from the effective fetch must be calculated. It proceeds as: replace t_{min} by t in Equation 12 and calculate the equivalent fetch length. The wave height and period can then be estimated by substituting equivalent fetch in the Equations 13 and 14[5,22].

The significant wave period (T_s) is sometimes multiplied by a constant to estimate peak period (T_p). Goda [25] suggested using a value of 1.05[15].

$$T_s \cong 1.05\, T_p \qquad ...(15)$$

The CEM Method

The minimum wind duration for accomplishing fetch limited condition is expressed as:

where t_{min} is the minimum wind duration (*s*) and *F* is fetch length (*m*) which was computed as the effective fetch length in this study. In the fetch limited case, the hindcast equations for non dimensional wave height and period are:

$$t_{min} = 77.23 \frac{F^{0.67}}{U_{10}^{0.34}\ g^{0.33}} \quad \text{... (16)}$$

$$\frac{g\,H_s}{U_*^2} = 4.13 \times 10^{-2} \left(\frac{g\,F}{U_*^2}\right)^{0.5} \quad \text{...(17)}$$

$$\frac{g\ T_p}{U_*} = 0.651 \left(\frac{g\,F}{U_*^2}\right)^{1/3} \quad \text{...(18)}$$

where U_* is the friction velocity (*m/s*) estimated as:

$$U_* = U_{10}\,(C_D)^{0.5} \quad \text{...(19)}$$

where C_D is the drag coefficient which is defined as [12]:

$$C_D = 0.001\,(1.1 + 0.035\,U_{10}) \quad \text{...(20)}$$

In duration limited conditions, equivalent fetch length is calculated as:

$$\frac{g\,F}{U_*^2} = 5.23 \times 10^{-3} \left(\frac{g\,t}{U_*}\right)^{1.5} \quad \text{...(21)}$$

In this equation, *t* is the wind duration (*s*). The equivalent fetch length estimated from this equation must then be substituted into Equations 17 and 18 to obtain estimates of wave height and period in duration limited case[5,12].

The JONSWAP Spectrum Method

The JONSWAP method predicts parametrically the integral wave parameters. These parameters are then used to define the spectrum, using the JONSWAP shape. This spectrum is frequently used to describe waves in a growing phase. The form of the spectrum is defined in terms of the peak frequency rather than the wind speed as [9]

$$E(f) = \alpha\, g^2\, (2\pi)^{-4}\, f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] \gamma^{\exp\left[-(f-f_p)^2/2\sigma^2 f_p^2\right]} \quad \text{...(22)}$$

where

$$\alpha = 0.076\left(g\,F\,U^{-2}\right)^{-0.22} \quad \text{...(23)}$$

$$f_p = \frac{3.5\,g\left(g\,F\,U^{-2}\right)^{-0.33}}{U} \quad \text{...(24)}$$

$$\sigma = \begin{cases} 0.07 & f < f_p \\ 0.09 & f \geq f_p \end{cases} \quad \text{...(25)}$$

f_p and U are the frequency of spectral peak and wind speed at 10 m above mean water level. The alpha sets the level of the high frequency tail and the gamma and sigma variables represent the peak enhancement of the spectral peak of the wind sea and the narrowness of this peak, respectively. The mean value of gamma during the JONSWAP experiment was observed to be 3.3. Significant wave height and zero-crossing wave period are defined for fetch-limited case as follows:

$$H_s = 0.0163\,F^{1/2}\,U \quad \text{...(26)}$$

$$T_z = 0.439\,F^{3/10}\,U^{2/5} \quad \text{...(27)}$$

and for duration-limited case,

$$H_s = 0.0146\,t^{5/7}\,U^{9/7} \quad \text{...(28)}$$

$$T_z = 0.419\,t^{3/7}\,U^{4/7} \quad \text{...(29)}$$

where H_s, T_z, *F*, and *t* are in *m*, *s*, *km*, and *h*, respectively. Fetch-limited formulations are appropriate if the following equation is satisfied.

$$t > 1.167\,F^{0.7} / U^{0.4} \quad \text{...(30)}$$

Otherwise, equations for duration-limited case are used [20,26].

Application of the parametric methods to the Black Sea

Four different parametric methods mentioned above sections were applied to the Black Sea using the ECMWF and TSMS wind data. Eight different model combinations for two wave parameters (significant wave height and mean wave period) in both stations (Hopa and Sinop stations) were separately constituted (Tables 3 and 4). Wave parameters (H_s and T_z) were estimated using wind data and parametric models, which were considered for Hopa and Sinop stations. For this process, wind speed and direction at 10 m elevation over the sea level in Hopa and Sinop stations were firstly determined for the TSMS wind data source by using Equations 1 and 2. Also, resultant wind velocity and direction in both stations for the ECMWF data set were calculated from wind components. The fetch lengths for all wind directions recorded at the stations in the ECMWF and TSMS data bases were determined as the effective fetch from Equation 3. Wind durations which are equal to number of consecutive hours were obtained from wind records as stated in section 3.2. Corresponding wind speeds and fetch lengths are also determined by taking their mean values over this duration (see Bishop [14] and Özger and sen[20]). Finally, wave hindcasts were performed from the time series of both data sources for two stations, and then, wave parameters were hindcasted by using two wind sources at Hopa and Sinop stations.

Buoy data used in this study has not regular temporal resolution and there are gaps in the records. On the other hand, wave hindcasts are performed from wind records with a certain temporal resolution. So, occurrence times of the hindcast data do not coincide with that of buoy data. In order to determine the statistical error indices, hindcast data must be

Table 3—Error statistics of parametric methods in the hindcasts of wave parameters for Hopa station

Data sources - Hindcast method	The number of concurrent data	Bias parameter	SI	RMSE	MAE	R	R^2
		Significant wave height (H_s, m)					
TSMS – JONSWAP	1083	-0.500	1.212	0.782	0.516	0.295	0.087
TSMS – CEM	(12 months)	-0.525	1.240	0.801	0.535	0.279	0.078
TSMS – SPM		-0.473	1.177	0.760	0.503	0.322	0.104
TSMS – Wilson		-0.489	1.180	0.762	0.501	0.389	0.151
ECMWF –JONSWAP	690	-0.401	1.188	0.640	0.424	0.322	0.104
ECMWF – CEM	(12 months)	-0.421	1.212	0.653	0.435	0.322	0.104
ECMWF – SPM		-0.395	1.178	0.634	0.424	0.334	0.112
ECMWF - Wilson		-0.451	1.246	0.670	0.454	0.399	0.159
		Mean wave period (T_z, s)					
TSMS – JONSWAP	1083	-2.486	0.735	2.847	2.533	0.014	0.000
TSMS – CEM	(12 months)	-3.000	0.832	3.223	3.000	0.021	0.000
TSMS – SPM		-2.513	0.733	2.840	2.538	0.033	0.001
TSMS – Wilson		-2.866	0.798	3.092	2.866	0.079	0.006
ECMWF –JONSWAP	690	-2.115	0.708	2.650	2.332	0.114	0.013
ECMWF – CEM	(12 months)	-2.755	0.803	3.007	2.760	0.120	0.014
ECMWF – SPM		-2.308	0.721	2.701	2.388	0.124	0.015
ECMWF - Wilson		-2.940	0.839	3.144	2.940	0.163	0.026

Table 4—Error statistics of parametric methods in the hindcasts of wave parameters for Sinop station

Data sources - Hindcast method	The number of concurrent data	Bias parameter	SI	RMSE	MAE	R	R^2
Significant wave height (H_s, m)							
TSMS – JONSWAP	461(10 months)	-0.491	0.903	0.991	0.704	0.285	0.081
TSMS – CEM		-0.550	0.937	1.023	0.742	0.272	0.074
TSMS – SPM		-0.263	0.962	1.056	0.718	0.317	0.100
TSMS – Wilson		-0.479	0.837	0.919	0.645	0.370	0.137
ECMWF – JONSWAP	426(10 months)	-0.496	1.054	0.956	0.580	0.304	0.092
ECMWF – CEM		-0.552	1.072	0.973	0.605	0.335	0.112
ECMWF – SPM		-0.409	1.048	0.951	0.575	0.293	0.086
ECMWF - Wilson		-0.625	1.125	1.021	0.650	0.308	0.095
Mean wave period (T_z, s)							
TSMS – JONSWAP	461(10 months)	-0.842	0.562	2.289	1.881	0.111	0.012
TSMS – CEM		-2.202	0.626	2.549	2.307	0.106	0.011
TSMS – SPM		-1.055	0.505	2.055	1.760	0.133	0.018
TSMS – Wilson		-2.006	0.568	2.313	2.068	0.193	0.037
ECMWF – JONSWAP	426(10 months)	-0.769	0.534	2.085	1.721	0.070	0.005
ECMWF – CEM		-2.112	0.618	2.409	2.157	0.085	0.007
ECMWF – SPM		-1.135	0.516	2.014	1.643	0.079	0.006
ECMWF - Wilson		-2.406	0.673	2.626	2.411	0.078	0.006

simultaneous with the buoy data. Therefore, buoy data and hindcasts are coupled.

For quantitative evaluation of the models, simultaneous buoy data and hindcasts were compared with each other. The error statistics of significant wave height and mean wave period predicted by parametric methods for Hopa and Sinop stations are presented in Tables 3 and 4. The scatter index (SI), bias parameter, root mean square error (RMSE), mean absolute error (MAE), correlation coefficient (R), and determination coefficient (R^2) were used to evaluate the degree of accuracy of the results. These statistical parameters were calculated as follows:

$$SI = \frac{RMSE}{\frac{1}{N}\sum_{i=1}^{N} O_i} \quad ...(31)$$

$$bias = \sum_{i=1}^{N} \frac{1}{N}\left(P_i - O_i\right) \quad ...(32)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(P_i - O_i\right)^2} \quad ...(33)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|P_i - O_i\right| \quad ...(34)$$

$$R = \frac{\sum_{i=1}^{N}\left(\left(P_i - \bar{P}\right)\left(O_i - \bar{O}\right)\right)}{\sqrt{\left(\sum_{i=1}^{N}\left(P_i - \bar{P}\right)^2\right)\left(\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2\right)}} \quad ...(35)$$

where O_i is the observed value, $\bar{O}$ is the mean value of the observed data, P_i is the predicted value,

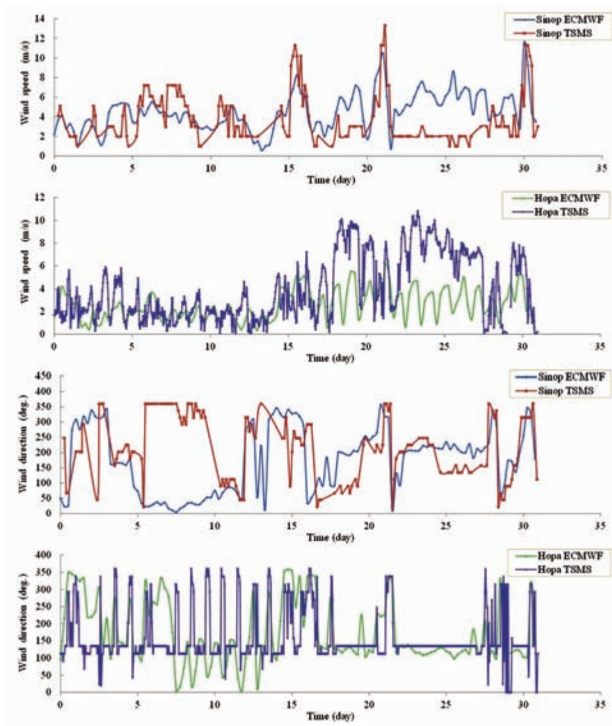
$\overline{P}$ is the mean value of the predicted data, and N is the number of data.

The performances of eight model combinations in the estimations of significant wave height and mean wave period can be seen in Tables 3 and 4. Although the results show that Wilson method is more accurate than other parametric methods and accuracy of the models is not in the desired level because R^2 and SI values of the hindcasts are much lower than 0.5 value. The possible reasons may be the measurement errors, unsuitability of parametric methods for the Black Sea, and the errors in determining the wind blowing duration. Besides, the source of the errors may also be the wind speed itself. Considering the buoy locations, the dominant wind direction, and the resolution of the atmospheric model, it is seen that winds blowing from land are strongly affected by land effects.

Since the parametric methods did not produced satisfactory results, it is decided to perform analyses for various values of the most appropriate critical angle of wind direction change which plays a limiting role in the determination of wind blowing duration. In the next section, a sensitivity analysis was carried out to determine the most appropriate value for the angle of direction change.

Sensitivity analysis for determination of the wind duration

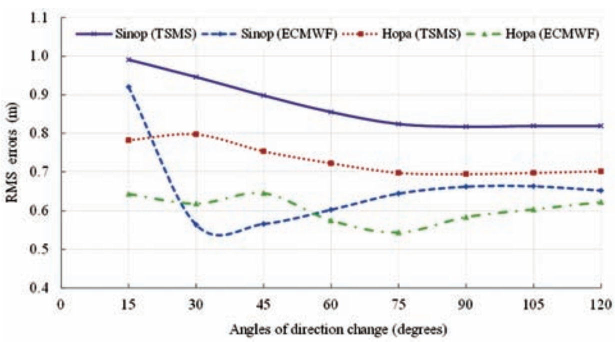
In wave hindcast methods, there are two criteria that control the procedure in the determining the wind blowing duration. The first one is the amount of change in the wind direction. It is assumed that the storm continues if the change in wind direction is less than a presumed value such as 15°, 30°, 45°, 90° etc. otherwise storms ends and a new storm starts. The time between the start and end of the storm is accepted as the wind duration. The second one is the amount of change in wind speed. If the change in wind speed is less than a given value (such as 2.5 m/s) then this means that storm continues [27]. When the wind records are examined (Figure 7), it is seen that while the change in wind speed is very low, the change in wind

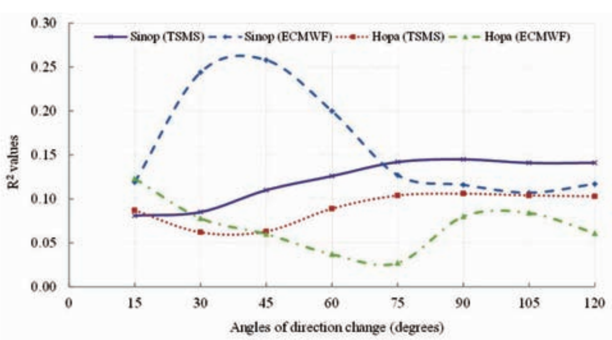


direction is significant. In other words, it is sensitive in determining of wind blowing duration. Therefore, it was decided to use wind direction as a selection rule in determining of wind duration. The most appropriate angle of wind direction change was searched for Hopa and Sinop stations, and for both wind data sources by comparing the measured and hindcasted data obtained by considering different angles of wind direction change.

In this study, to determine the wind duration, eight different values 15°, 30°, 45°, 60°, 75°, 90°, 105°, and 120° as the value of the critical wind direction change angle were investigated. Wind durations were determined separately for all angles of direction change from the time series of the ECMWF and TSMS data recorded at Hopa and Sinop stations. Afterwards, corresponding wind speeds and directions and fetch lengths are also determined by taking their mean values over these durations. The JONSWAP method that is the most widely used parametric wave hindcast method was selected to make estimations of wave characteristics. Wave hindcasts were performed for the ECMWF and TSMS data bases at Hopa and Sinop stations in the observation period. After the hindcasts were carried out, for the appropriate comparison, concurrent data of buoy measurements and hindcast values determined for all angles of direction change was obtained. The most appropriate angles of wind direction change for the ECMWF and TSMS data set recorded in both stations were discussed and determined by using RMSE values and correlations between buoy measurements and wave hindcasts calculated for different angles of wind direction change. Figures 8 and 9 show variations in the RMSE and R^2 values related to the estimates of significant wave height carried out by using two different wind data sources for various angles of wind direction change at two stations.

As can be seen from Figures 8 and 9, the lowest RMSE and the highest R^2 values for the wave estimates from TSMS wind data at Sinop station are obtained for the critical angle of 90 degrees of direction change. For this critical angle, the R^2 and





RMSE values were 0.145 and 0.817 m. The wave hindcasts using the ECMWF wind data at the same station have the lowest RMSE (0.566) and the highest R^2 values (0.258) for the critical angle of 45 degrees of direction change. Besides, it is seen from Figure 10 that the correlations between buoy measurements and wave hindcasts performed by using the critical angle of 45 and 90 degrees of direction change determined for the ECMWF and TSMS data sets at the Sinop station are much better than that of other angles of wind direction change.

At Hopa station, it was observed that wave hindcasts using TSMS wind data have the lowest error (0.694) in the 90 degrees of direction change while it was the 75 degrees for the ECMWF wind data. However, it was observed that the lowest error in the wave hindcasts using the ECMWF wind data at the Hopa station was the angle of the 75 degrees of wind direction change and the best coefficient of determination was obtained from wave hindcasts used the 15^o angle of direction change. The scattering diagrams showing the relationships between the buoy measurements and wave hindcasts obtained for different critical angle of wind direction change are presented in Figure 10.

In light of all these considerations, four wave models (TSMS-JONSWAP, TSMS-SPM, TSMS-CEM, and TSMS-Wilson models) for Hopa and Sinop stations were employed by taking the critical angle of direction change as 90 degrees for the TSMS wind data. In the same way, four wave models (ECMWF-JONSWAP, ECMWF-SPM, ECMWF-CEM, and ECMWF-Wilson models) for Hopa station were employed by taking the critical angle of direction change as 15 degrees for the ECMWF wind data and the models for Sinop station were established by using 45 degrees as determining criteria of the wind blowing duration for the ECMWF wind data.

It was found that the most appropriate angle of wind direction change for obtaining the best estimations of the wave parameters from TSMS wind data base in the Middle and Eastern Black Sea was the 90 degrees. Also, Sahin *et al*[27] determined that the most appropriate angle of wind direction change to obtain the best wave hindcast results from the TSMS data in the Western Black Sea was the 90 degrees[28].

Results and Discussions

Performance evaluation of parametric methods in the Black Sea

The critical angle for wind direction change was determined for each station using sensitivity analysis in the implementation of parametric methods. By considering this critical angles wave hindcasts were carried out using ECMWF and TSMS wind data at Hopa and Sinop stations. Predicted and observed wave parameters were compared to each other. Tables 5 and 6 present the error statistics for concurrent hindcasts and buoy measurements at Hopa and Sinop stations. As can be seen from these tables, the models using the ECMWF wind source have lower RMSE values and correlation coefficients than the models using the TSMS wind data for hindcasts of significant wave height at Hopa station. In contrast to this, in hindcasts of mean wave period for the same station, it was observed that the models using the ECMWF wind source have higher RMSE values and correlation coefficients than the models using the TSMS wind data. At Sinop station, it is seen that RMSE values of the models using the ECMWF wind source are lower than that of the models using the TSMS wind data for both wave parameters. But, while correlation coefficients of the models using the ECMWF wind source are higher than that of the models using the TSMS wind data for significant wave height, it is lower for mean wave period. Also, it is understood that the SPM method using the ECMWF wind data has better results (RMSE=0.634 m and R=0.334) for hindcasts of significant wave height while performance of the CEM method using the TSMS wind data is better (RMSE=2.038 s and R=0.047) than that of the other methods for mean wave period at Hopa station. Also, It is observed for Sinop station that the CEM method using the ECMWF wind data has better results (RMSE=0.533 m and R=0.563 for H_s and RMSE=1.478 s and R=0.048 for T_z) for hindcasts of both wave parameters. Besides, it can be say that error and correlation values of all models are close to each other. Therefore, time series of hindcasts of H_s and T_z from parametric methods were also discussed. A comparison of time series of hindcasts of H_s and T_z from parametric methods with buoy data for two stations is also illustrated in Figures 11 and 12. As can be seen from this figures, the Jonswap and Wilson methods has low hindcasts of wave parameters while the SPM method has generally hindcasts close to buoy data. Also, it is observed from these figures that the CEM method compared to other methods mostly produces more accurate results in the hindcasts of wave parameters for both wind sources in both stations. Storms in time series of wave parameters measured in buoy stations were observed in the model estimations. In addition to, the results of the models using the ECMWF wind source at Hopa station are significantly low. However, at Sinop station, this situation is not seen. This may be due to orography effects. .

Proposed models for the Black Sea

Performance evaluations of the classical wave hindcast methods for the Black Sea show that parametric wave hindcast models are not in the desired level of accuracy (because R values of the hindcasts are lower than 0.7 value) for the study area. The best wave hindcast method developed has very low R^2 values (max. R^2=0.195 for H_s and 0.026 for T_z at Hopa station and 0.331 for H_s and 0.040 for T_z at Sinop station) and higher errors (min. RMSE=0.634 m for H_s and 2.038 s for T_z at Hopa station and 0.533 m for H_s and 1.478 s for T_z at Sinop station) as can be seen from Tables 5 and 6. Therefore, in this part of the study, new models which can represent the wave conditions in the southern coasts of the Black Sea with higher correlation coefficient and lower error compared to the classical wave hindcast methods were proposed to predict the wave parameters. For this purpose, different combinations were studied as follows:

- The constants found in the equations of the classical methods were re-determined by using measured data for Hopa and Sinop stations. For instance, the JONSWAP method was considered as follows for fetch- and duration-limited cases:

Table 5—Error statistics of concurrent data of hindcasted wave parameters with the buoy measurementsat Hopa station

Data source – Hindcast method	Critical angle of direction change (degrees)	Significant wave height (H_s, m)		Mean wave period (T_z, s)	
		RMSE value	R	RMSE value	R
TSMS – JONSWAP	90	0.694	0.327	2.511	0.033
TSMS – CEM		0.744	0.419	2.038	0.047
TSMS – SPM		0.880	0.439	2.504	0.027
TSMS – Wilson		0.684	0.442	2.824	0.078
ECMWF – JONSWAP	15	0.640	0.322	2.650	0.114
ECMWF – CEM		0.653	0.322	3.007	0.120
ECMWF – SPM		0.634	0.334	2.701	0.124
ECMWF - Wilson		0.670	0.399	3.144	0.163

Table 6—Error statistics of concurrent data of hindcasted wave parameters with the buoy measurements at Sinop station

Data source – Hindcast method	Critical angle of direction change (degrees)	Significant wave height (H_s, m)		Mean wave period (T_z, s)	
		RMSE value	R	RMSE value	R
TSMS – JONSWAP	90	0.817	0.380	2.457	0.091
TSMS – CEM		1.040	0.500	1.624	0.175
TSMS – SPM		1.382	0.466	2.550	0.202
TSMS – Wilson		0.756	0.425	2.593	0.123
ECMWF – JONSWAP	45	0.566	0.508	2.144	0.016
ECMWF – CEM		0.533	0.563	1.478	0.048
ECMWF – SPM		0.589	0.576	1.778	0.066
ECMWF - Wilson		0.655	0.552	2.500	0.053

where a, b, c, d, e, and f constants were optimized based on the measured data of both stations. The constants of above equations were re-determined by using the ECMWF wind source at Hopa station. But, correlation coefficient of the developed model was not enhanced by comparison the existing Jonswap equations. The developed model had R=0.30 but correlation coefficient of Jonswap method was 0.32. Besides, the performance of the developed model for the fetch and duration limited cases was investigated. Correlation coefficients for fetch and duration limited cases were 0.11 and 0.30, respectively. From this, it was understood that the developed model has great errors for fetch limited condition compared to duration limited case. This may be due to 45^o range used for the concept of effective fetch. Then, the performance of the developed model was discussed for other wind source (TSMS) and other station (Sinop). It was found that the developed model has worse performance than the Jonswap method for both cases.

- The constants of the equation used for t_{min} calculation in the JONSWAP method were also determined by assigning different values to develop equations having lower errors and higher correlation coefficients for both stations. However, no improvement was achieved.

From the results of above two steps, it is shown that more the proposed models can not produce more accurate wave hindcasts than existing methods.

- Since the results from first two steps are not at desired level. Different functions such as weibull, fourier, gauss, polynomial, sinus, exponential, and power type functions were fitted using linear and nonlinear least squares techniques. The generated equations were applied to the other station to obtain a general equation being valid for both stations. It is seen that the fitted models have better performances compared to parametric wave hindcast models at the station which its data is used for calibration. However, same model gives worse results at other station.
- Curve fitting was also performed by using different x and y variables (for example y = H/U and x = t for duration-limited condition and y = H and x = F/U for fetch-limited condition). The results can not be improved so much. Similar results were obtained with abovementioned regression models.
- The scenarios mentioned above steps were repeated for the dataset covering the all data of two stations. However, no improvement was achieved.
- Finally, average and standard deviation of data were calculated for each station. Curve fitting was performed by using the remaining data in the band created by adding and subtracting standard deviation from the average value. The purpose of this pre-processing is to create smoother curves. Results of equations generated in this way have not been achieved efficiently to represent all southern coasts of the Black Sea by comparison the existing parametric methods.

It is concluded that while the proposed model decreased scatter index, but the correlation coefficient was not enhanced. These results show that application of such simplified methods or parametric models does not improve model performance along the south coasts of the Black Sea. Third-generation wave models like SWAN model[29] are systematically used world-wide both for research and engineering applications with extremely accurate results. On the other hand, it is well recognized that third generations wave models perform extremely well provided the wind fields are accurate enough. Therefore, academicians and engineers interested in the study area should tend to implementation of these models rather than application of simplified methods for activities in this area.

Conclusions

In this study, the accuracy of the parametric wave hindcast methods such as Wilson, SPM, JONSWAP, and CEM models was investigated by using two different wind sources at two locations in the Black Sea. Totally 32 different parametric wave models were tried for both significant wave height and mean wave period hindcast. Results reveal that Wilson method is the most accurate model compared to other parametric methods for the initial analysis. It is also seen that parametric wave models are not at the desired level of accuracy for wave parameters hindcast.. In the light of determined critical angles of wind direction change for each station and wind source, it is found that the CEM method compared to other methods generally produces more accurate results in the hindcasts of wave parameters in both stations. Hindcasts of significant wave height are better than that of mean wave period in terms of correlation coefficients. The newly proposed model decreased scatter index, but the correlation coefficient was not enhanced and the desired level of accuracy was not obtained. CEM method can be used in extremely simple practical applications. It is suggested to academicians and engineers working in the field of interest of this study that they should tend to implementation of developed numerical models (e.g. third generation wave models – SWAN) rather than application of parametric methods for important coastal engineering design activities in this area.

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References

1 Moeini, M.H., Etemad-Shahidi, A., Application of two numerical models for wave hindcasting in Lake Erie, *Applied Ocean Research*, 29 (2007) 137-145.

2 Kazeminezhad, M.H., Etemad-Shahidi, A., Mousavi, S.J., Evaluation of neuro fuzzy and numerical wave prediction models in Lake Ontario, *Journal of Coastal Research*, Special Issue, 50 (2007) 317-321.

3 Browne, M., Castelle, B., Strauss, D., Tomlinson, R., Blumenstein, M., Lane, C., Near-shore swell estimation from a global wind-wave model: spectral process, linear, and artificial neural network models. *Coastal Engineering*, 54 (2007) 445-460.

4 Goda, Y., Revisiting Wilson's formulas for simplified wind-wave prediction. *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE, 129 (2003) 93-95.

5 Etemad-Shahidi, A., Kazeminezhad, M.H., Mousavi, S.J., On the prediction of wave parameters using simplified methods, *Journal of Coastal Research*, Special Issue, 56 (2009) 505-509.

6 Pierson, W.J., Moskowitz, L., A proposed spectral form for fully developed seas based on the similarity theory of S.A. Kitaigorodskii. *Journal of Geophysical Research*, 69 (1964) 5181–5191.

7 Wilson, B.W., Numerical prediction of ocean waves in the North Atlantic for December, 1959, *Ocean Dynamics*, 18 (1965) 114-130.

8 Bretschneider, C.L., Wave forecasting relations for wave generation. Look Lab, Hawaii, 1 (3), 1970.

9 Hasselmann, K., Barnett, T.P., Bouws, E., Carlson, H., Cartwright, D.E., Enke, K., Ewing, J.A., Gienapp, H., Hasselmann, D.E., Kruseman, P., Meerburg, A., Mller, P., Olbers, D.J., Richter, K., Sell, W., Walden, H., Measurements of wind-wave growth and swell decay during the joint North Sea wave project (JONSWAP). Ergnzungsheftzur Deutschen Hydrographischen Zeitschrift Reihe, Deutsches Hydrographisches Institute, Hamburg, Germany, 1973.

10 Donelan, M.A., Similarity theory applied to the forecasting of wave heights, periods and directions, paper presented at the *Canadian Coastal Conference* (Canada), pp. 47-61, 1980.

11 U.S. Army, Shore Protection Manual, U.S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, Fourth Edition – No. 20402, Washington (DC), USA, 1984.

12 U.S. Army, Coastal Engineering Manual, Chapter II-2, Meteorology and Wave Climate, U.S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, No. EM 1110-2-1100, Washington (DC), USA, 2003.

13 Kazeminezhad, M.H., Etemad-Shahidi, A., Mousavi, S.J., Application of fuzzy inference system in the prediction of wave parameters, *Ocean Engineering*, 32 (2005) 1709-1725.

14 Bishop, C.T., Comparison of manual wave prediction models. *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, 109 (1983) 1-17.

15 Bishop, C.T., Donelan, M.A., Kahma, K.K., Shore protection manual's wave prediction reviewed. *Coastal Engineering*, 17 (1992) 25-48.

16 Moeini, M.H., Etemad-Shahidi, A., Evaluation of SWAN numerical model & SPM method for wave hindcasting, paper presented at the *7th International Conference on coasts, ports and marine structures* (Tehran, Iran), pp. 416-422, 2006**.**

17 Akpinar, A., Kömürcü, M.I., Özger, M., Kankal, M., The application of SWAN for wave simulation in Black Sea, paper presented at *the 7th National Coastal Engineering Conference* (Trabzon, Turkey), pp. 269-280, 2011 (in Turkish).

18 Ergin, A., *Coastal Engineering*, Ankara, Turkey: METU Press, No. 9789944344821, 392p, 2009.

19 Hsu, S.A., On the correction of land-based wind measurements for oceanographic applications, paper presented at *the 17th International Conference on Coastal Engineering -ASCE* (Sydney, Australia), pp. 708-724, 1980.

20 Özger, M., Sen, Z., Triple diagram method for the prediction of wave height and period. Technical Notes. *Ocean Engineering*, 34 (2007) 1060-1068.

21 Reeve, D., Chadwick, A., Fleming C., Coastal Engineering: Processes, theory, and design practice. Spon Press, Taylor and Francis Group, London and New York, 2004.

22 Yüksel, Y., Çevik, E.Ö., Coastal Engineering. Istanbul, Turkey: Beta Publishing Inc., Marine Engineering Series– No. 1, 732p, 2009 (in Turkish).

23 Ozeren, Y., Wren, D.G., Predicting wind-driven waves in small reservoirs, Technical Note, *Trans. ASABE*, 52 (2009) 1213-1221.

24 Liu, Z., Frigaard, P., Generation and analysis of random waves, Laboratoriet for Hydraulik og Havnebygning, Instituttet for Vand, Jord og Miljoteknik, Aalborg Universitet, Denmark, 2001.

25 Goda, Y., *Random seas and design of maritime structures*. University of Tokyo Press, 323p, 1985.

26 Özger, M., Wave energy prediction and stochastic modeling. Ph.D. Thesis, Istanbul Technical University, Istanbul, Turkey, 2007 (in Turkish).

27 Sahin, C., Aydogan, B., Çevik, E., Yüksel Y., Parametric wave modeling with wave data of south-west Black Sea, paper presented at the *VI. National Coastal Engineering Conference* (Izmir, Turkey), pp. 249-256, 2007 (in Turkish).

28 Akpinar, A., Wave modeling and wave energy potential determination in the Black Sea. Ph.D. Thesis, Karadeniz Technical University, Trabzon, Turkey, 2012 (in Turkish).

29 Booij, N., Holthuijsen, L.H., Ris, R.C., A third-generation wave model for coastal regions. 1. Model description and validation, *Journal of Geophysical Research*, 104 (1999) 7649-7666.