EVALUATION OF THE WAVE CLIMATE OVER THE BLACK SEA: FIELD OBSERVATIONS AND MODELING

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The knowledge of the wave climate is one of the most important data for application of coastal engineering, which includes coastal structure design, sediment transport, coastal erosion and so on. Due to the lack of measurements in many region and high cost of wave measurements, coastal engineers have to estimate wave characteristics using a variety of methods, which comprise empirical and numerical solutions. A variety of empirical and numerical methods have been developed and used for determining wave characteristics. In this study, in order to determine wave climate over the Black Sea, it was used third generation Mike 21 spectral wave model. For this purpose, a series of numerical models were conducted in a way to cover the 13-year period between 1996 and 2008. The obtained results from numerical models were compared to the results of Wind and Deep Water Wave Atlas for Turkish Coasts. It was concluded that the results were highly consistent each other.

Keywords: Mike 21 SW, Wave Climate of the Black Sea

INTRODUCTION

During the last decades, the countries that have border on the Black Sea have needed wind and wave climate of the Black Sea. So scientists have conducted a lot of scientific efforts to determine the wind and wave climate of the Black Sea (Cherneva et al 2008). The knowledge of the wave climate is one of the most important data for application of coastal engineering, which includes coastal structure design, sediment transport, coastal erosion and so on. Due to the lack of measurements in many region and high cost of wave measurements, coastal engineers have to estimate wave characteristics using a variety of methods, which comprise empirical and numerical solutions.

The wave prediction methods can be classified as early methods, spectral models and numerical wave models. By using the simple empirical methods or spectral models to predict the wind generated waves are required selection of the representative values of wind speed, fetch and duration (Sorensen, 2006). A variety of empirical methods have been developed and used for determining wave characteristics by using mathematical formulas.

The simple wave prediction formulas based on rough observations were in use. With the coming of the Second World War, Sverdrup and Munk (1947) developed a wave prediction method. This procedure included relatively simple wave energy growth concepts with empirical calibration using the small amount of available data. Afterwards Bretschneider (1958) improved this procedure. This method was called SMB method after these studies. There are also a variety of empirical methods such as JONSWAP, Shore Protection Manual and Coastal Engineering Manual etc.

In the last two decades, there has been a strong effort to develop numerical models for wave prediction. Generally, these models are based on a numerical integration over a spatial grid of the spectral energy balance equation (Sorensen 2006). These numerical models are able to represent the complex physical processes that include generation and transformation of waves.

A variety of studies have been carried out to determine the wind and wave climate of the Black Sea. The first international research project about the Black Sea Wave Climate was NATO TU-WAVE Project. The wave models were carried out by using METU3 Wave Model and WAM. The time spanning for long-term and extreme statistics was 8 and 20 years, respectively (Özhan and Abdalla 1998).

Cherneva et al. 2008 have been represented the validation of the WAM Cycle 4 (WAMC4) numerical model for the Black Sea. For this purpose, the WAM Cycle 4 (WAMC4) numerical model was run and the results of a 41-year wave hindcast for the period 1985-1998 applied to obtain the

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regime of wind and wave characteristics of the Black Sea. It was concluded that agreement of the WAMC4 numerical model results and measured data sets were highly compatible with each other.

Another numerical model studies performed by Cavaleri et al. 1999 were investigated the wind and wave climate of the Black Sea. A 7-year hindcast was conducted using surface wind fields data received from European Center for Medium-Range Weather Forecasts. The model results were validated and calibrated using TOPEX Satellite altimeter data.

Vledder and Akpınar 2015 performed another wave climate study using by SWAN wave model. In this study, ECMWF Interim wind data was used as well.

The aim of the present study is to determine the wind and wave climate of the whole Black Sea by using third generation wave model Mike 21 Spectral Wave. The results of this study is expected to serve as a helpful guide for management of coastal zones in the Black Sea and for engineering applications (e.g., for estimation of design wave parameters for coastal structures, determination of locations with high wave energy potential and renewable energy studies).

STUDY AREA

The present study is focused on the whole Black Sea, which is located between 40° 56’ - 46° 33’ North latitudes and 27° 27’ - 41° 42’ East longitudes. This semi-closed sea is connected to the Sea of Marmara and Aegean Sea through the Bosporus and Dardanelles straits respectively. And there is also connection to the Sea of Azov by strait of Kerch. It can be seen study area from satellite image, which is given in the Figure-1. The Black Sea has a surface area of 461 thousand square kilometers which is included Sea of Azov. The Black Sea has the maximum depth of 2588 m and mean depth of 1300 m.

Figure-1 The Study Area

MATERIALS and METHODS

Wave Model Description

In order to determine wind and wave climate of the whole Black Sea, it was used to third generation spectral wind-wave model Mike 21 Spectral Wave numerical model. Mike 21 SW can be used to determine wave climates in offshore and coastal areas in hindcast and forecast mode as well. The major application area of the Mike 21 Spectral Wave model is the design of offshore, coastal and port structures.

This new generation wind-wave spectral model is based on unstructured meshes. The numerical model can be simulated the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas. Mike 21 SW scientific background is based on two types of formulations. These formulations are directional decoupled parametric formulation and fully spectral formulation. When using directional decoupled parametric formulation, the parameterization of the wave action conservation equation is utilized. When using another formulation, the calculation is based on the wave action conservation equation where the directional-frequency wave action spectrum is the dependent variable.

The conservation equation for wave action in horizontal Cartesian co-ordinates can be expressed by using following equation.

$$\frac{\partial N}{\partial t} + \nabla(\vec{v}N) = \frac{S}{\sigma} \qquad (1)$$

In Equation (1), $N(\vec{x},\sigma,\theta,t)$ is represented action density, t is the time, $\vec{x} = (x, y)$ is the Cartesian co-ordinates, $\vec{v} = (c_x, c_y, c_\sigma, c_\theta)$ is the propagation velocity of a wave group in the four-dimensional phase space, ∇ is represented the four-dimensional differential operator in the $\vec{x},\sigma,\theta$ space. S term in Equation (1) is represented source term for the energy balance equation. This term is the superposition of source functions, which have description various physical phenomena. The source term can be expressed by using following equation.

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{sur} \qquad (2)$$

In Equation (2), S_{in} is represented the generation of energy by wind, S_{nl} is expressed the wave energy transfer due to non-linear wave-wave interaction, S_{ds} is the dissipation of wave energy due to white capping, S_{bot} is represented the dissipation due to bottom friction and the last term of the source function S_{sur} is the dissipation of wave energy due to depth-induced wave breaking. Detailed information about Mike 21 Spectral Wave scientific background can be found in DHI 2008.

Buoy Data

In present study, it was needed to measurement data to calibrate the numerical model of the Black Sea. In this context, a series of measurement data including different time of span was used for calibration of the numerical models. For this purpose, five directional wave buoys were deployed at Hopa, Sinop, Filyos, Karaburun offshore the Turkish Coast and at Gelendzhik on the Russian Coast. It can be seen characteristics of the buoy locations and measurement dates in the following table (See Table-1) (Özhan and Abdalla 1998). It can be seen locations of wave measurement stations from Figure-2.

Table-1 Characteristics of the Measurement Stations

Name of Station	Latitude (N)	Longitude (E)	Water Depth (m)	Distance From Shore (m)	Data Period
Hopa	41˚ 25' 24"	41˚ 23' 00"	100	4600	October 1996 – April 1999
Sinop	42˚ 07' 24"	35˚ 05' 12"	100	11600	January 1996 – June 1996
Filyos	41˚ 60' 00"	32˚ 02' 00"	100	-	December 1995 – December 1996
Karaburun	41˚ 21' 00"	28˚ 41' 00"	16	-	August 2003 – December 2004
Gelendzhik	44˚ 30' 27"	37˚ 58' 42"	85	7000	July 1996 – December 2003

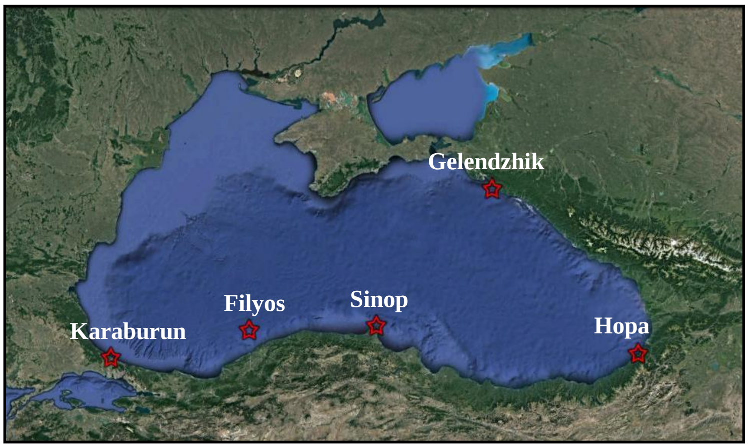

Figure-2 Locations of Wave Measurement Stations

Wind Data

Wind data required for the wave modeling study, with a spatial resolution of 0.1°x0.1° and temporal resolution of 6 hours, which was analyzed by means of ERA analysis model of ECMWF (The European Centre for Medium-Range Weather Forecasts) based in London.

Bathymetry

Nautical charts developed by the Office of Navigation, Hydrography, and Oceanography of the Turkish Naval Forces Command were digitized and used in the studies of determining wave climate of the Black Sea. This computational domain is covered the whole Black Sea from 41° Lat. to 47° Lat. and from 27° Long. to 42° Long. A fairly fine mesh including 4755 nodes and 8213 elements were used to determine the wave and wind climate of the Black Sea. It can be seen computational domain of the Black Sea from Figure-3.

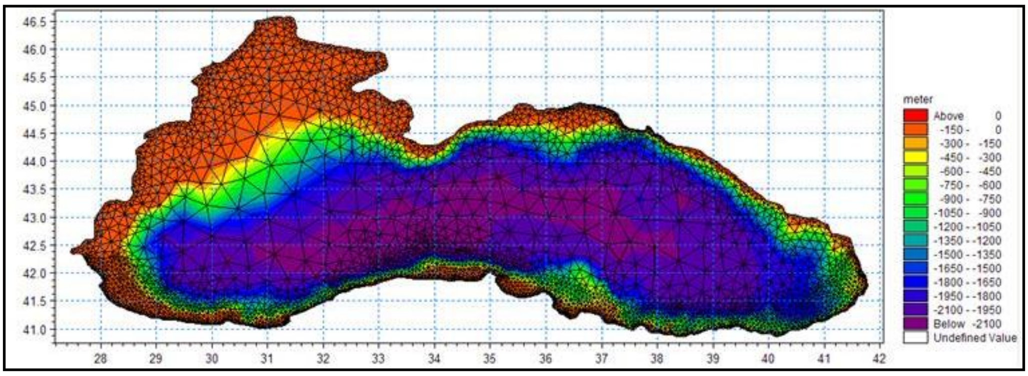

Figure-3 Computational Domain of the Black Sea

Numerical Model Set-up and Calibration

The spectral wave model was implemented on the whole Black Sea using by third generation wave model Mike 21 SW. Wave characteristics of the Black Sea were hindcasted from 1996 to 2008 for a 13 year time span. Trial and error method was used in the calibration process. A series of numerical models were run and model results were compared with significant wave height (m) and mean wave period (s) obtained from wave measurement stations at Hopa, Sinop, Filyos, Karaburun and Gelendhzik. Time histories is showed good agreement between measured data and numerical model results. The numerical model studies were estimated significant wave height (m) better than mean wave peirod (s). It can be seen that the numerical model is overestimated mean wave period (s) about 15%.

In order to evaluate the numerical model results, Root Mean Square Error (RMSE), Correlation Coefficient (R), Bias (BIAS) and Scattering Index (SI) were used. These formulations can be seen from Equation (3) to Equation (6) respectively.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - 0_i)^2}{N}} \quad (3)$$

$$R = \frac{\sum_{i=1}^{N}(P_i - \overline{P})(O_i - \overline{O})}{\sqrt{\sum_{i=1}^{N}(P_i - \overline{P})^2 \sum_{i=1}^{N}(O_i - \overline{O})^2}} \quad (4)$$

$$BIAS = \sum_{i=1}^{N}\frac{1}{N}(P_i - O_i) \quad (5)$$

$$SI = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2}}{\frac{1}{N}\sum_{i=1}^{N}O_i} x100 \quad (6)$$

Where N is represented the total number of data, O_i is represented the measured value, P_i is the predicted value calculated from numerical model. Overbar is indicates mean value. It can be seen Root Mean Square Error (RMSE), Correlation Coefficient (R), Bias (BIAS) and scattering index values, which obtained from calibration process from following table (See Table-2).

Table-2 Statistics Values Obtained from Calibration Process

Measurement Stations	H_s (m)				T_m (s)			
	RMSE (m)	R	BIAS (m)	SI	RMSE (s)	R	BIAS (s)	SI
Hopa	0.30	0.80	0.04	53.86	1.21	0.62	0.67	30.45
Sinop	0.36	0.77	0.07	45.67	0.98	0.71	0.59	25.74
Filyos	0.43	0.79	0.26	71.86	NR*	NR*	NR*	NR*
Karaburun	0.35	0.92	0.19	44.83	0.56	0.86	0.23	15.23
Gelendhzik	0.30	0.89	-0.02	41.44	0.83	0.82	0.48	23.59
Average	0.35	0.83	0.11	51.53	0.90	0.75	0.49	23.75

(*) means Not Reliable.

Bottom friction, breaking (γ) and white-capping calibration parameters, used in the model calibration, were found 0.8, 0.04 and 0.5 respectively. These calibration parameters' values were obtained after a series of numerical model studies. Trial and error method was also used in this process.

Numerical Model Results

The numerical model was conducted in a way to cover the 13-year period between 1996 and 2008. The model results obtained were compared to the results of Wind and Deep Water Wave Atlas for Turkish Coasts (Özhan and Abdalla 2002). It was seen that the results were highly compatiblewith each other.

9 points were selected in order to determine the wave climate of the different regions of the Black Sea. Locations of these 9 points are given in the Figure-4. Additionally, wave roses were obtained with the purpose of identifying the wave climate of the Black Sea (Saraçoğlu 2011). It can be seen wave roses in Figure-5.

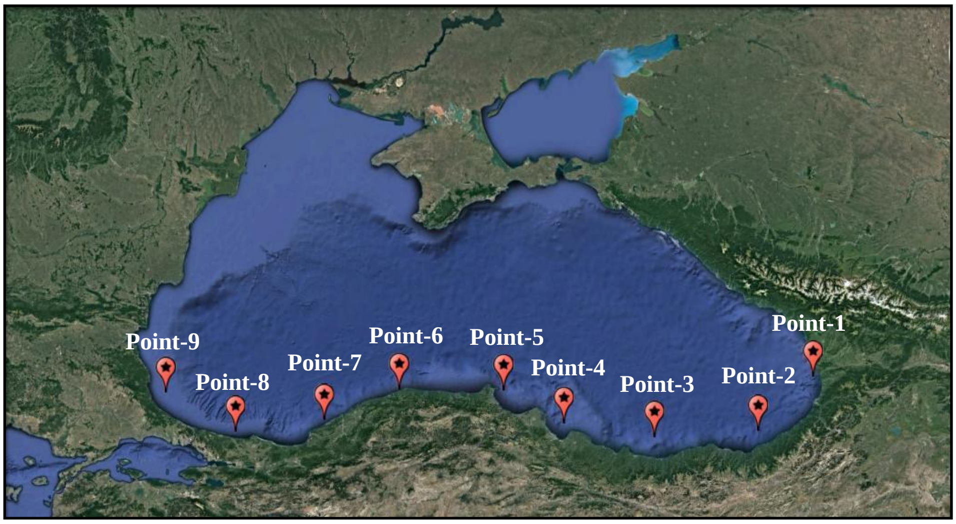

Figure-4 Location of the Selected 9 Points

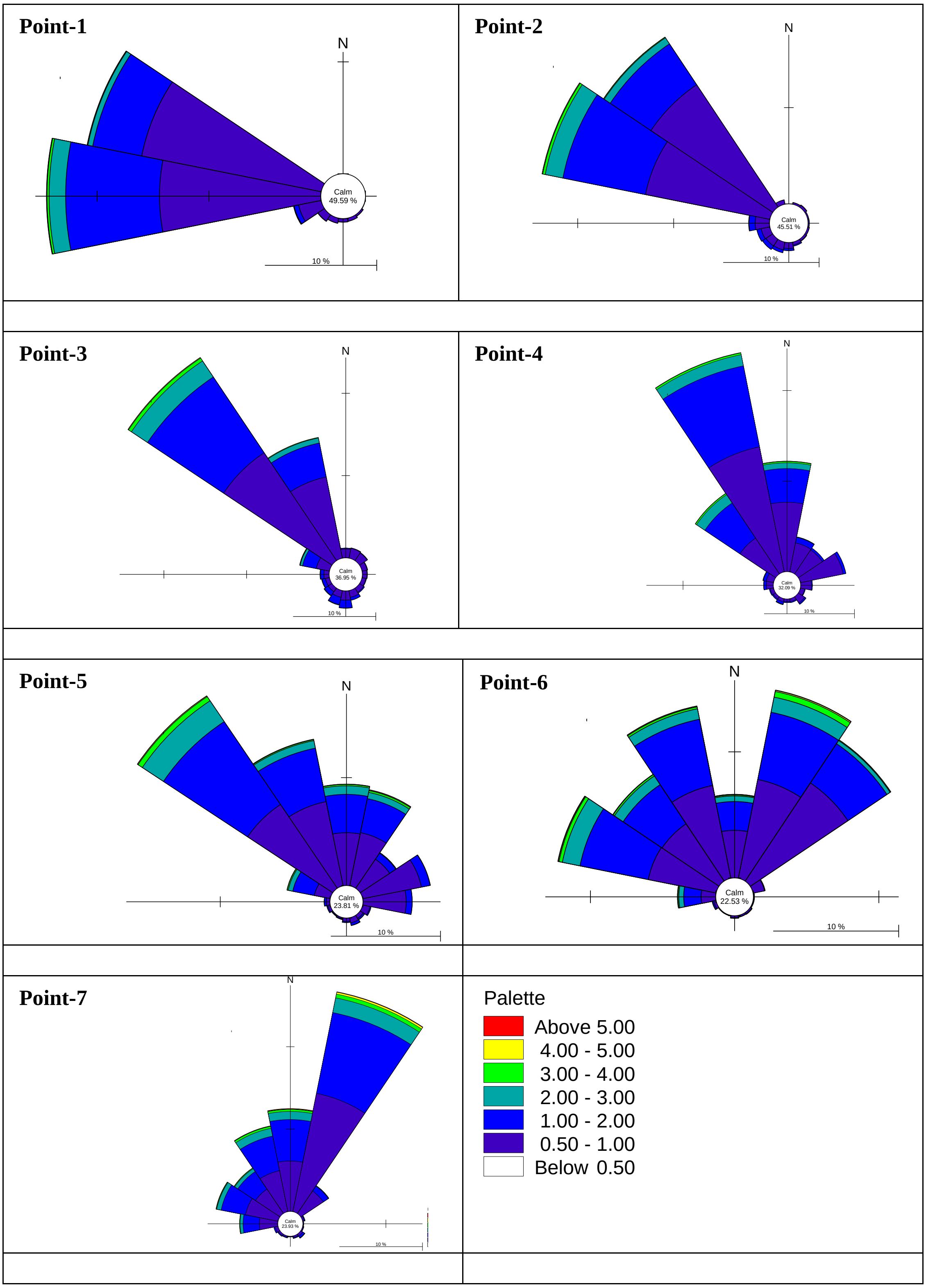

Figure-5 Wave Roses for Selected Points

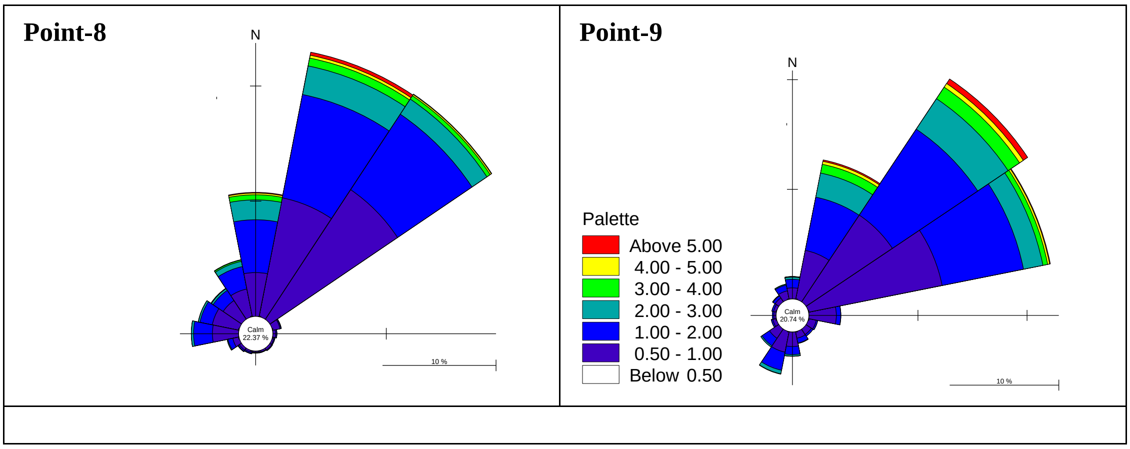

Figure-5 Wave Roses for Selected Points (Continued)

As shown in Figure-5, for the Point-1, Point-2 and Point-3 which represent the eastern part of the Black Sea, waves come from W, WNW and NW directions dominantly. For Point-4 and Point-5, majority of waves come from NW, NNW directions. When it is taken into account Point-6, waves come from northern directions. For Point-7, Point-8 and Point-9, dominant wave directions are NE, NNE. Additionally, Wave roses show that for most of the time of the numerical modeling duration, significant wave height values are below 2.5 m.

CONCLUSIONS

In this present study, numerical models were conducted for the period of 1996-2008 by using Mike 21 SW, a third generation wave-wind model, in order to determine the wave climate of the Black Sea. The obtained results from numerical modeling were compared to the results of Wind and Deep Water Wave Atlas for Turkish Coasts. It can be seen clearly that the model and the Wind and Deep Water Wave Atlas for Turkish Coasts' results are highly consistent. As a result of the modeling studies, it was determined that deep water significant wave heights range between quiescent state and 10 m and mean wave periods between 2 s and 10 s.

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