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Application of a numerical model for wave parameter hindcasting in the Marmara Sea Basin

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Abstract

One of the most important factors in design of coastal and marine structures is to determine the wave characteristics precisely. In this paper, wave characteristics of Sea of Marmara obtained during the time span between 1994 and 2014 by using the third generation spectral model MIKE 21 SW. Wind data was obtained from ECMWF ERA-Interim re-analyses wind dataset with a spatial resolution of 0.125 degree. The numerical model was calibrated with a wave data that measured for 1 year (2013) by measurement buoy on the Southern coast near the Istanbul in the Sea of Marmara. Numerical mesh optimization was also performed to obtain the most suitable domain to overcome the time efficiency problem in running time of the model. This research is recently amongst the first studies that deal with the determination of wave parameters in the Marmara Sea Basin. In addition, the relation between significant wave height and wave period is established. The results reveal that wave prediction capacity of the numerical model gives satisfactory results.

Keywords: *Sea of Marmara, MIKE 21 SW, wave parameter hindcasting, ECMWF ERA-Interim re-analyses, numerical mesh optimization.*

Marmara Denizinde dalga parametresi tahmini için sayısal modelin uygulanması

Öz

Kıyı ve deniz yapılarının tasarımında en önemli faktörlerden biri dalga özelliklerinin minimum hata ile belirlenmesidir. Bu çalışmada, 1994-2014 yılları arasında Marmara Denizi'nin dalga özellikleri, üçüncü nesil spektral bir model olan MIKE 21 SW kullanılarak elde edilmiştir. Bu modelde kullanılan Rüzgâr verileri, 0.125 derecelik bir

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uzamsal çözünürlüğe sahip olan ECMWF ERA-Interim rüzgâr veri setidir. Sayısal model, Marmara Denizi'nde İstanbul yakınlarında bulunan Güney kıyısındaki ölçüm şamandırası ile 1 yıl (2013) için ölçülen dalga verileri ile kalibre edilmiştir. Modelin çalışma süresindeki zaman verimliliği sorununun üstesinden gelmek için sayısal ağ optimizasyonu gerçekleştirilmiştir. Bu araştırma son zamanlarda Marmara Denizi Havzası'nda dalga parametrelerinin belirlenmesi ile ilgili ilk çalışmalar arasındadır. Ayrıca, belirgin dalga yüksekliği ve dalga periyodu arasındaki ilişkiler elde edilmiştir. Sonuçlar, sayısal modelin dalga tahmin kapasitesinin tatmin edici sonuçlar verdiğini ortaya koymaktadır.

Anahtar kelimeler: *Marmara Denizi, MIKE 21 SW, dalga parametresi tahmini, ECMWF ERA-Interim re-analyses, sayısal ağ optimizasyonu.*

1. Introduction

The Sea of Marmara, located between the Black Sea and the Aegean Sea, is an important sea for ocean engineering activities. The Marmara Sea is connected to the Aegean Sea through the Dardanelles Strait and is connected to the Black Sea through the Bosporus Strait. Dardanelles and Bosporus straits help maintain the balance between water supply and evaporation. Ergin et. al., [1], indicated that the flux rate of suspended solids for the Dardanelles and the Bosporus Straits are, 9.0×105 tons/yr and 14.5×105 tons/yr, respectively.

Abdollahzadehmoradi et al. [2], using MIKE 21 SW to obtain wave energy potential of the Marmara Sea. In that study, numerical model forced with ECMWF wind data with a resolution of 0.125° in both longitude and latitude. MIKE 21 SW model was calibrated by using the measured wave parameters (2 monthes). The maximum annual significant wave heights are calculated as 0.48m in those regions for the year 2012.

Demyshev and Dovgaya [3], mentioned that the dynamics of the Straits of Bosporus and Dardanel attracted considerable attention in recent years. The project coordinated by the NATO Undersea Research Centre. However, studies on the numerical modeling of the general circulation of the Sea of Marmara is nearly absent and significantly idealized. Sea of Marmara can be considered as a buffer zone between Black Sea and the Mediterranean Sea that they are two different ecosystems. Numerical model that used for running model is the Regional Ocean Modeling System (ROMS).

Over the years, the hydrodynamics of the Turkish Straits have been observed and analyzed through extensive and systematic monitoring and project-based measurement campaigns. The quasi-steady modeling of the Istanbul Strait is performed by Özsoy et. al., [4]. The modelling approach involves many specific assumptions, simplifications and parameter tuning for the particular case The results show that how the system responds to varying forcing at the surface and the two exits. Oğuz and Sur [5], deals with a steady state two-layer modelling approach. The authors focused on the analysis of the contributions of the various process terms along the geometric constrictions and sills of the strait.

Kutupoğlu et al. [6] predicted wave conditions of the Marmara Sea by using SWAN. The model results were calibrated by the using of wave measurements by TPAO in 2013. The

results show that the SWAN model forced with the ERA Interim winds has better results than the SWAN model forced with the CFSR winds.
SWAN model was used in a similar study by Erdik and Beji [7], to obtaine wave climate for the Marmara Sea. In that paper, most frequent significant wave height was found to be 0.25 m and wave period as 4 s.

There are several studies on the determination of wave climate and energy potential in several seas worldwide using numerous modelling methods. Jose and Stone [8], used MIKE 21SW to employ wind speed data of National Center for Environmental Prediction (NCEP) on a daily basis to estimate wave parameters and stated that there is a good agreement between observations and predictions. As for extreme weather conditions, predictions are relatively higher than observations. Akpınar and Kömürcü [9], used SWAN to study the wave energy resource of the Black Sea. In the study, the authors used ECMWF ERA Interim wind fields for a period of 15 years (1995-2009) and obtained the mean annual wave energy resource in the Black Sea as up to 3 kW/m. In another study, Rusu and Guedes Soares [10], investigated the spatial distribution of the wave energy on the northern and central parts of the Portuguese coastline. They also used SWAN as a numerical model and the model system simulated for a 40-day period. Abdollahzadehmoradi et. Al. [11], obtained wave power potential of the Marmara Sea by using MIKE 21 SW based on 20 years ECMWF ERA Interim wind data set (1994-2014). The third generation spectral model MIKE 21 SW was calibrated and validated by using one-year measured wave dataset of buoy. The monthly, seasonal and annual spatial distribution of the maximum mean significant wave height and the wave power flux were extracted from the simulated data.

The main purpose of this study, is to establish the wave height hindcasting of the Marmara Sea. ECMWF Wind data with a spatial resolution of 0.125 covering the time span between 1994 and 2014 is employed. As indicated in this section, this research is recently one of the first studies that deal with the determination of wave parameters in the Marmara Sea Basin.

This paper begins with a brief about the case study, bathymetry data, and MESH element optimization. Following this, the calibration process is given in Section 3. Extreme value analysis presented after wave conditions of the Marmara Sea in Section 5. Finally, a brief summary of the main results from this work is provided in Section 6.

2. Study area and field data

The Marmara Sea, located in latitudes between 40.2° N and 41.1° N and longitudes between 26.5° E and 30° E in the Northern hemisphere, is a small continental sea located between the Aegean and the Black Sea, connected to these seas by the Dardanelles and the Bosphorus Straits, respectively. The surface area is 11,350 km² (280 km × 80 km) with the largest depth reaching 1,370 m (Fig. 1).

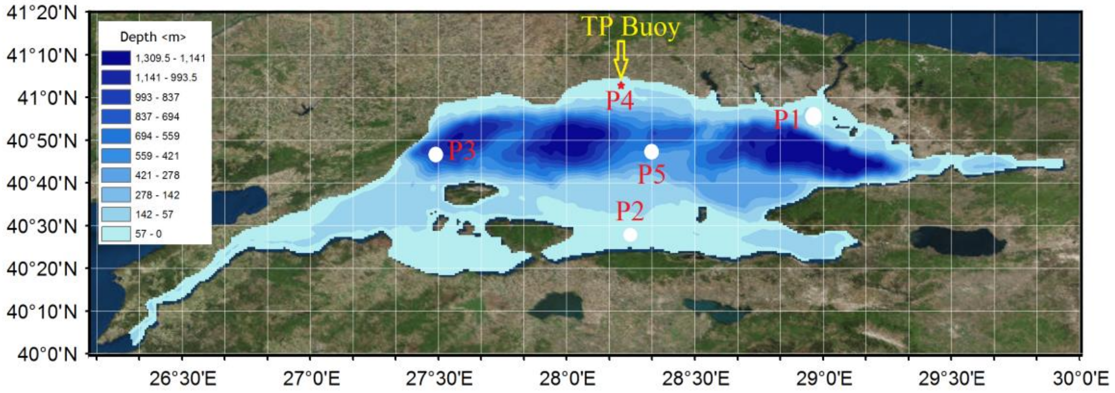

Figure 1. The plan view, TP and 5 observation points location in Marmara Sea Basin.

Measured wave data were collected from the buoy, operated by Turkish Petroleum (TP) (Fig. 1.). The buoy, located at 41°02'37.98" N and 28°11'12.77" E at a depth of 50 m, collected data within the period of February 2013 to January 2014 with a time resolution of 30 minutes. The location of the buoy is depicted as a red star in Fig. 1. Significant wave height (SWH), mean wave period (MWP) and mean wave direction (MWD) parameters were measured during the one-year operation period. Fig. 2. shows the wave rose of the measured wave data.

From the wave rose for wave direction frequency it is seen that the waves predominantly come from the S-E band with a probability of 27%. In other words, the dominant wave direction is South-East. On the other hand, the maximum wave height shows a quite diverse distribution, reaching 1.25 m in S direction.

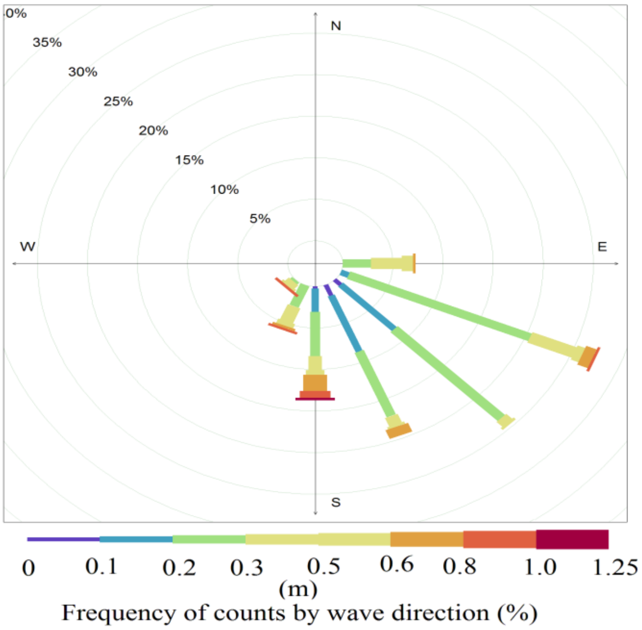

Figure 2. Obtained wave rose.

The descriptive statistics of the buoy measured parameters (Significant Wave Height (SWH), Maximum Wave Height (Max. WH), Wave Direction (WD), Wave Period (WP) and Peak Wave Period (Peak WP)) is given in Table 1. As can be seen from Fig. 1, the Marmara Sea is an inland sea with a calm environment.

Table 1. Descriptive statistics of the wave data measured at TP buoy.

	SWH (m)	Max. WH (m)	WD (Deg.)	WP Tm02 (s)	WP Tm01 (s)	Peak WP (s)
Maximum	1.25	1.78	359.30	5.81	7.59	23.19
Average	0.33	0.27	141.89	3.65	4.24	13.12
Minimum	0.04	0.00	0.70	0.06	3.05	3.36
Standard Deviation	0.21	0.29	52.43	0.94	0.79	5.78

2.1. Bathymetry data and MESH element optimization

The bathymetry data were obtained from the online data source of “Marine Geoscience Data System (MGDS)”. The resolution of the bathymetry data is obtained at 15 arc-second in x and y axes. MIKE 21 SW uses flexible mesh to establish the spectral waves model. In the mesh generator module of the MIKE, the user can produce a large number of mesh with the variable number of elements and nodes. Mesh size is important for convergence and stability. In this study, the optimum mesh size was determined to get maximum efficiency with a short time. The model run time depends on the number of elements and, thus, the optimized number of elements of flexible mesh is needed to avoid large run-time durations [11].

The simulated significant wave height values obtained for each model at the 5 points (Fig 1) and the coefficient of determination (R2) was used as evaluation criteria of the relationship between the results are shown in Figure 3. The R2 was determined by considering values of significant wave height computed by considering (M1 and M2), (M2 and M3), (M3 and M4), (M4 and M5), (M5 and M6), and (M6 and M7). Similarly, R2 values are expected after a certain number of mesh elements if the number of elements does not have a further effect on the performance of the model.
The equation of the coefficient of determination is given below.

$$R^2 = 1 - \frac{\sum(S_i - O_i)^2}{\sum(O_i - \bar{O})^2 + \sum(S_i - O_i)^2} \tag{1}$$

where S_i is the simulated value, O_i is the observed value, $\bar{O}$ is the mean of the observed values.

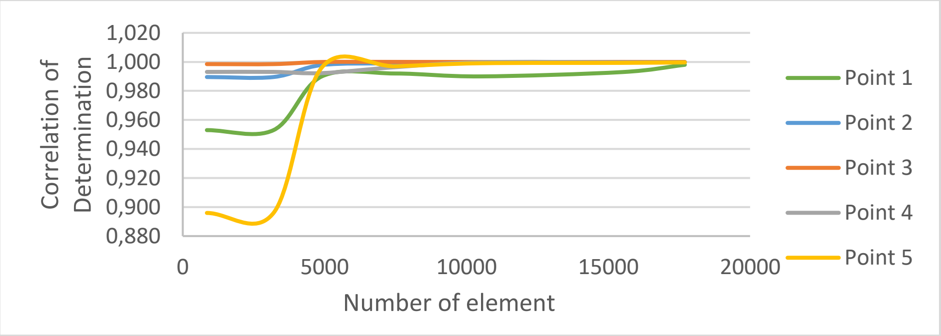

Figure 3. R^2 of 5 different points with various flexible mesh.

As can be seen from Figure 3, there are no notable changes after the use of the mesh with 4892 elements. Therefore, it is convenient to use the mesh with 4892 elements in the model to meet the objective of the study. The optimum mesh structure is shown in Fig. 4.

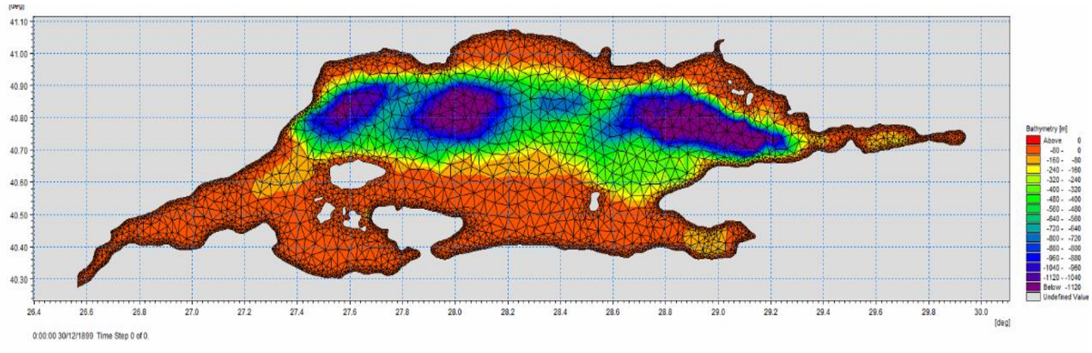

Figure 4. Optimized mesh for the Marmara Sea wave model.

3. Calibration process

ECMWF ERA-Interim re-analyses wind dataset with a spatial resolution of 0.125 degrees (this is the best resolution in ECMWF ERA-Interim re-analyses wind dataset) for the year, 2013 used for model calibration. The calibration of the models was carried out based on widely used statistical error criteria as Correlation coefficient (r) and the Root Mean Square Error, given below, respectively.

$$r = \frac{\sum_{i=1}^{N}(S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N}(S_i - \bar{S})^2 \sum_{i=1}^{N}(O_i - \bar{O})^2}} \tag{2}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2} \tag{3}$$

where S_i is the results of the simulation, O_i is the observation value, $\bar{O}$, is the mean of the observed values $\bar{S}$, is the average of the simulated values, and N is the total number of data.

The effective parameters on the wave properties are found to be as Whitecapping, wave breaking (Gamma) and background Charnock parameter for calibration purposes. Whitecapping (Cdis and DELTAdis) is directly related to the process of wave growth. Wave breaking (Gamma) is related to water depth and the interaction of input wind. The growth rate of the waves generated by wind depends also on the wave age because of the dependence of the aerodynamic drag on the sea state. The background Charnock parameter is related to Sea surface roughness (wind stress). It is noteworthy that bottom friction was not used for calibration because the measurement buoy is located in depth area which is independent of bottom friction effect.

20 scenarios were prepared with a combination of C_{dis}, $DELTA_{dis}$, Gamma and Background Charnock parameters, and the measured data were compared with the model results by statistical parameters described above. The calibration is performed by employing TP buoy data for one year long, which covers the period from February 1,

2013, to January 23, 2014. The calibrated values for the best model for Gamma, C_{dis}, $DELTA_{dis}$, Charnock parameters were found as 1.59, 1, 0.1, 0.008 respectively.

The time series graph with measured and observed values for TP Buoy is shown in Figure 5. And a good agreement was found between the measured and the modeled values in terms of significant wave height. A scatter diagram with a linear regression line is demonstrated in Fig. 6. with R^2= 0.75 and RMSE =0.16 m.

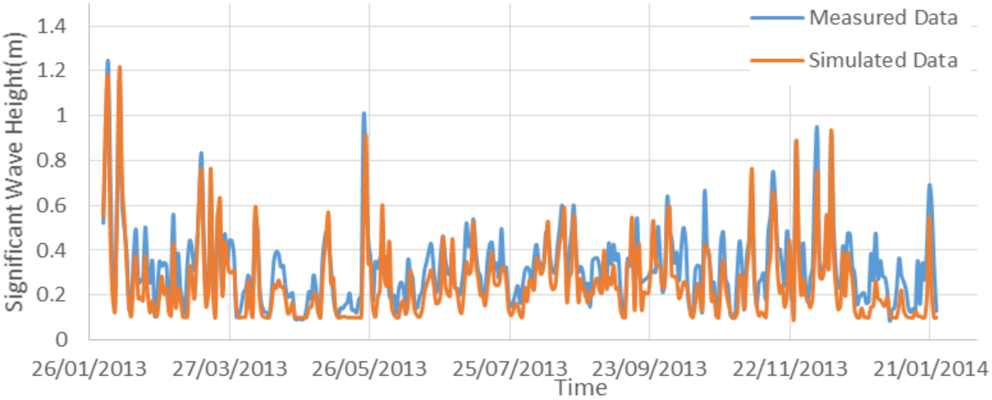

Figure 5. Comparison of simulated and measured significant wave heights from February 1, 2013 to January 23, 2014.

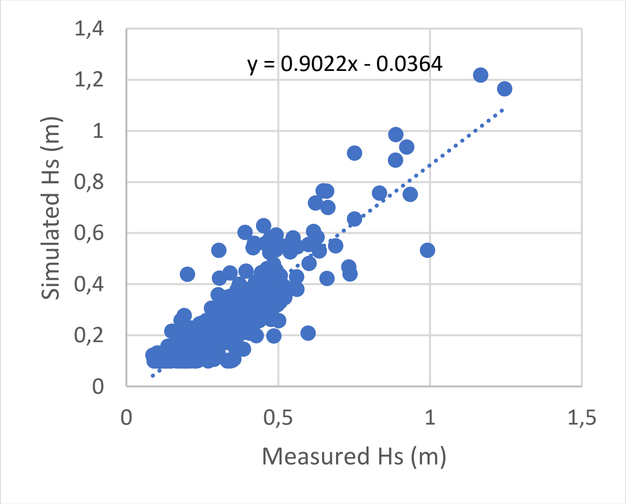

Figure 6. Linear regression analyses of simulated and measured significant wave heights from February 1, 2013 to January 23, 2014.

The prediction capability of the wave model in terms of wave direction is also good. Fig. 7. shows a time series distribution of measured and predicted wave directions. The numerical prediction capacity is calculated as 0.71 for r (Fig. 8.). The measured and predicted wave period is demonstrated in Fig. 9. The prediction capacity is a bit low compared to others with r=0.45.

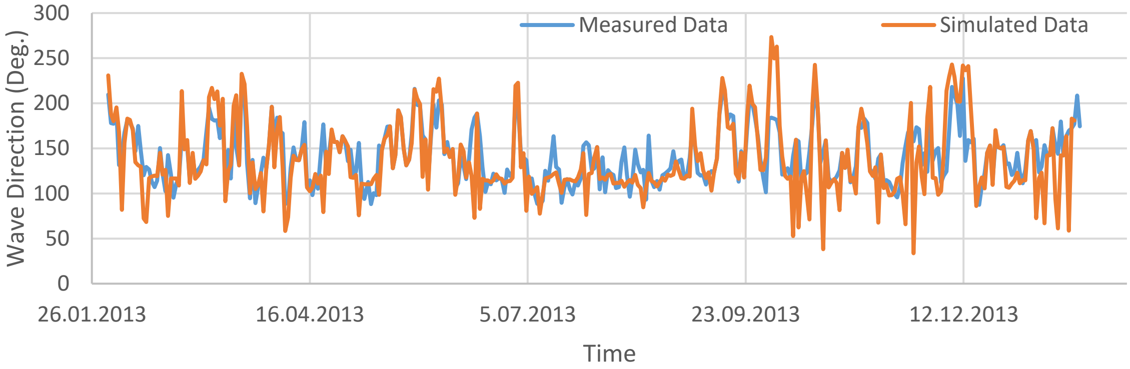

Figure 7. Comparison of simulated and measured Wave directions from February 1, 2013 to January 23, 2014.

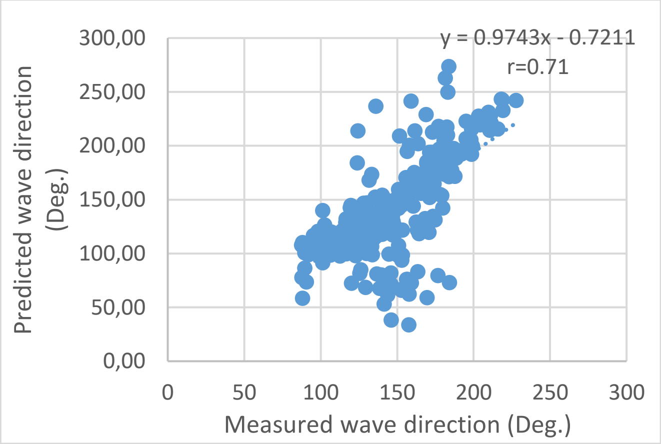

Figure 8. Comparison of simulated and measured wave direction from February 1, 2013 to January 23, 2014.

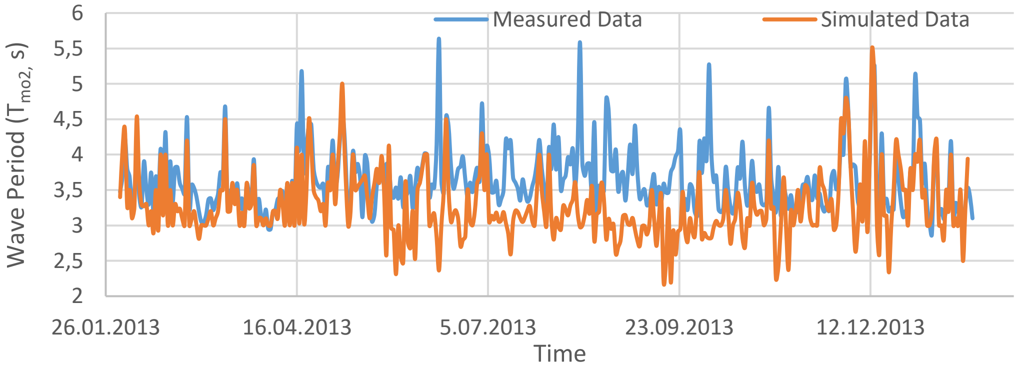

Figure 9. Comparison of simulated and measured T_{mo2} from February 1, 2013 to January 23, 2014.

Generally, the MIKE 21 SW successfully estimates Hs and wave direction however, it underestimates T_{m02}.

4. Wave conditions of Marmara Sea

In order to give a better perspective on the representative wave conditions in Sea of Marmara, long term analysis based on ECMWF data is presented in this section. A total of 5 uniformly distributed points across the Marmara Sea Basin (as shown in Fig. 1) were selected for depth analysis, 4 of them are located nearshore and 1 point offshore. The scatter plots of Hs and Tm with regression equations are depicted in Fig 10. The average R^2 value for the regression equation was found to be 0.65.

Wave roses produced for each considered point covering 20 years' model results are given in Fig. 11, in which waves are predominantly coming from northeastern directions except point 4, where the main wave direction has moved to the western direction. Point 3 receives heights waves with an average value of 0.338 m, while point 4 minimum waves with 0.273 m. The wave heights were calculated as very low. This implies that waves are sheltered by lands around.

5. Extreme value analysis

The extreme value analysis was carried out in order to assess the statistical performances of the points across the Marmara Sea. Goda [12], indicated that the Gumble and Weibull statistical distributions are the best distributions for wind and wave. Similarly, the Weibull distribution function is found to be better fitted than others by using Kolomogrov and Smirnov test in this research. The cumulative distribution functions of the points are calculated and drawn in Fig. 12. The 10% probability of occurrence value was also calculated. Those values were 0.75 m, 0.8 m, 0.83 m, 0.78 m and 0.8 m for the points 1-5, respectively. It is seen that wave heights are more or less uniformly distributed. In addition, a 10% probability of occurrence mapping of the Marmara Sea basin was also calculated by using 21 points across the sea (Fig. 13.). It was observed that middle parts have high significant wave height which reaches nearly 2.5 m.

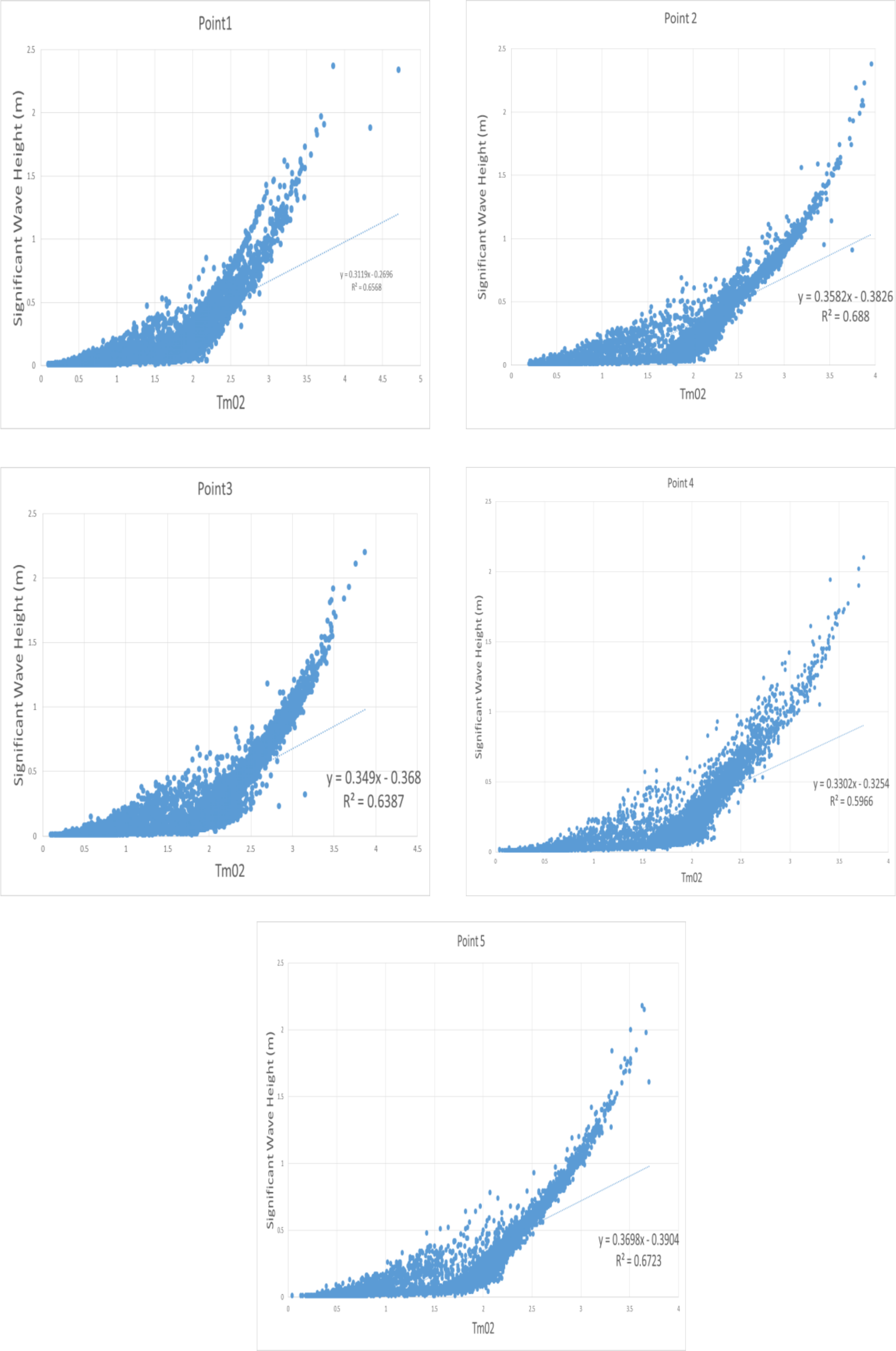

Figure 10. Distribution of H_s versus T_{m02}.

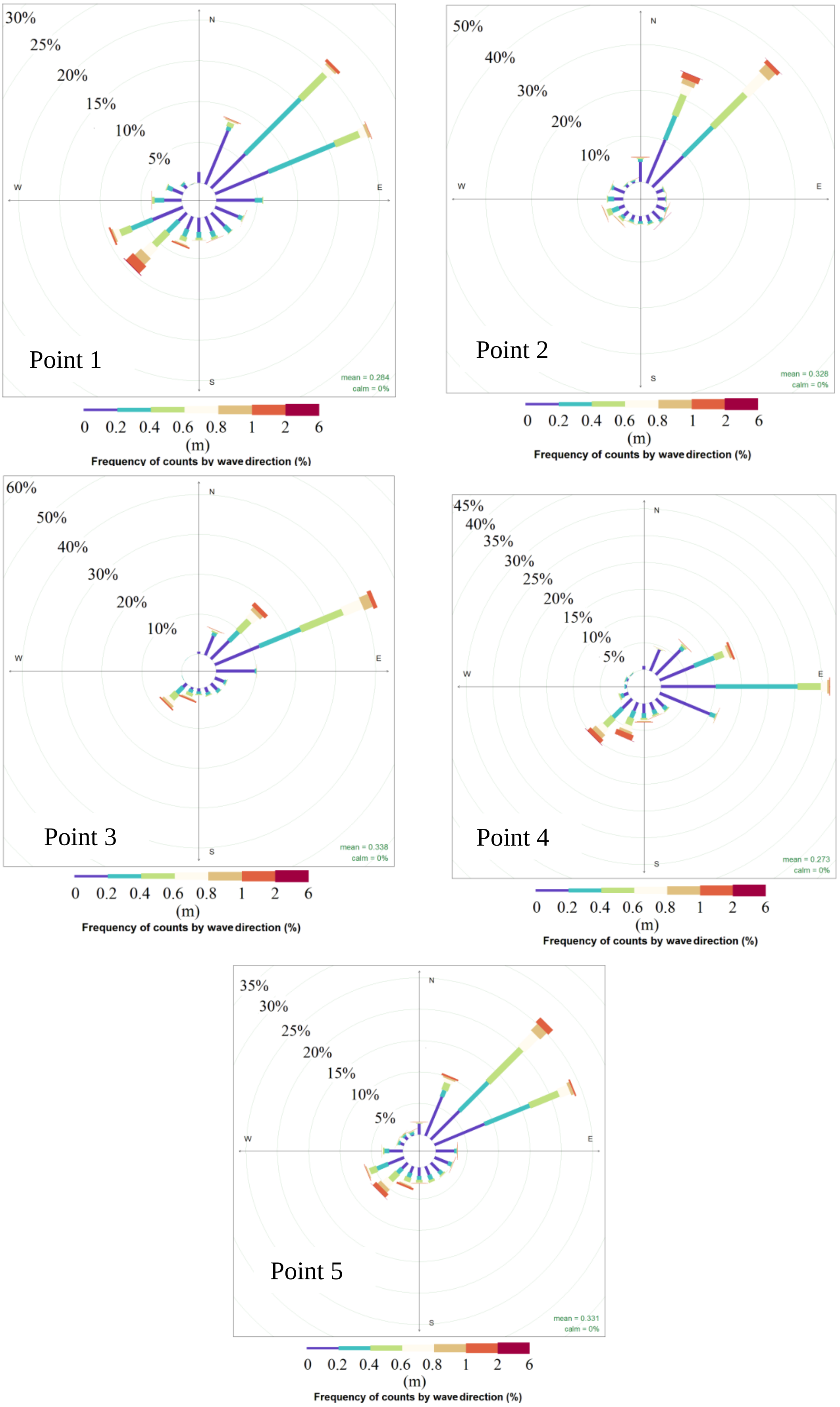

Figure 11. Wave roses for each considered point covering 20 years model results.

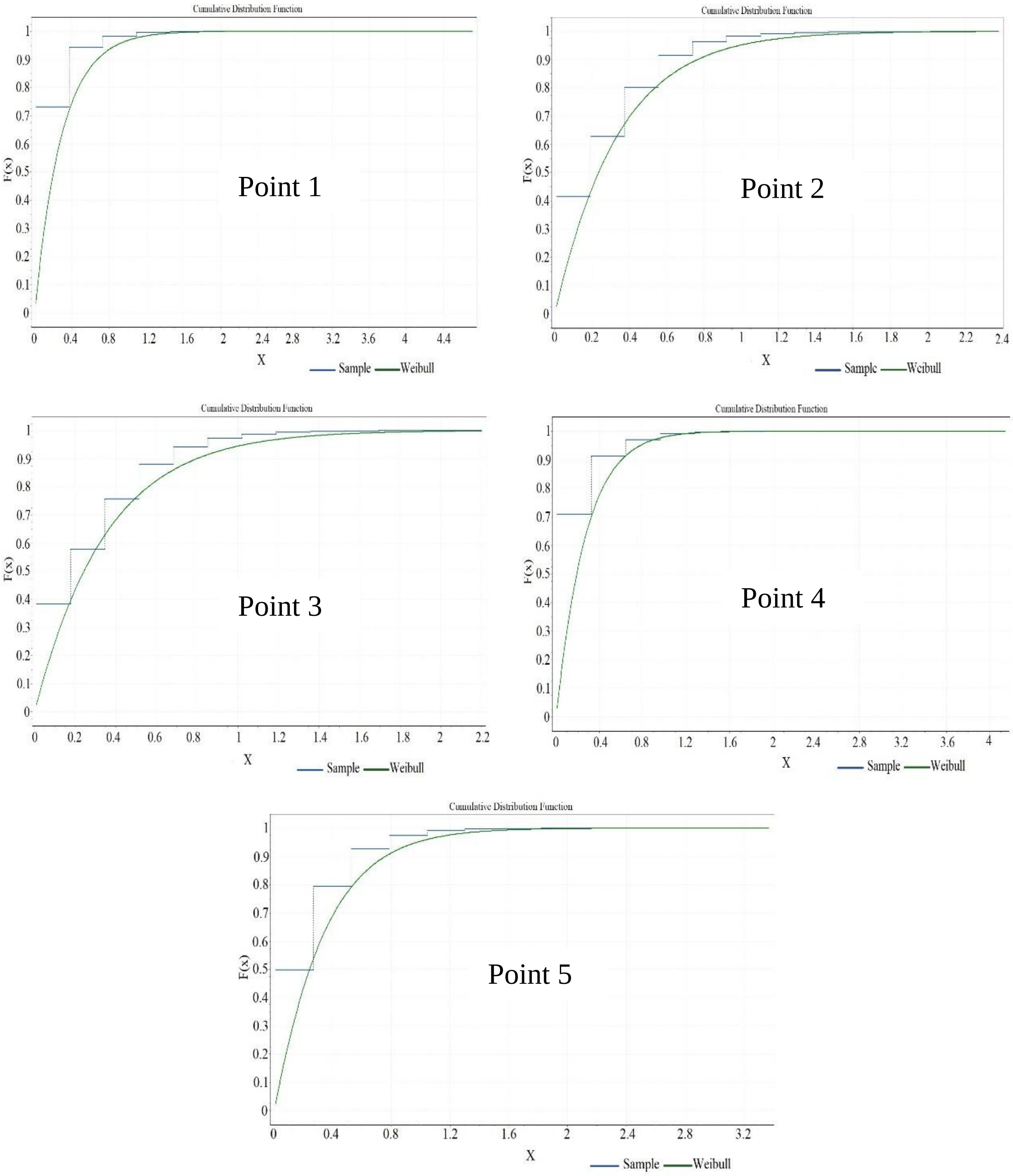

Figure 12. Cumulative distribution functions for the points in the Marmara Sea Basin.

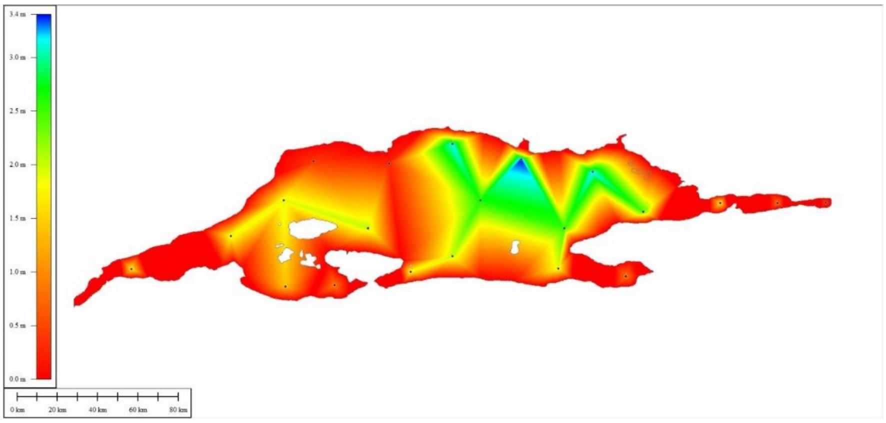

Figure 13. Spatial distribution of wave heights with 10% probability of occurrence.

6. Conclusions

In this research, wave hindcasting in Marmara Sea Basin was carried out. For this purpose, a 20-yearly ECMWF wind field was used as the input for the MIKE 21 SW model which is calibrated with the TP buoy station of one-year long. Mesh optimization was performed to obtain the most accurate results in terms of time efficiency.

The results indicated the high accuracy of modeling of the wave characteristics in the Marmara Sea Basin. In addition, the relation between significant wave height and wave period was established and cumulative distribution graphs and spatial distribution of wave heights with a 10% probability of occurrence were drawn. Based on the results of the study, it was concluded that the middle part of the Marmara Sea is more energetic than other part.

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