A COMPUTATIONAL TOOL FOR WIND WAVE PREDICTION BASED ON CEM METHOD

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

A COMPUTATIONAL TOOL FOR WIND WAVE PREDICTION BASED ON CEM METHOD

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In this study, a computational tool is presented for the wind wave prediction based on the CEM Method. The method is given for the computation of storm-averaged wind wave characteristics. The computational tool utilizes the hourly average wind speed and direction and the effective fetch data for a geographical location to compute the hourly significant wave height and period and the mean direction. In the study, the main focus is given on identifying the individual storms and the individual storm durations considered in the computation of hourly wind wave characteristics. The computational tool is applied to two locations in the Mediterranean Sea, where the wind and wave buoy measurements are available. The individual storms are identified based on three main parameters: minimum wind speed, maximum hourly wind speed change and maximum hourly wind direction change. In the study, several ranges are defined for these parameters and the effect of the values of these parameters on identifying storms and the resulting wind wave characteristics are given and discussed. Also, in the computation of hourly wind wave characteristics, several approaches are considered. These are briefly listed as; the continuous data, storm-based with user-defined duration and storm-based with storm duration. The results of hourly averaged wind wave characteristics for these approaches are presented with respective error statistics. The best approach is observed to be the storm-based user-defined duration approach. In the study, for the locations considered, it is observed that the user-defined duration is related to the wind climate of the location.

Keywords: Wave Prediction, Parametric Modelling, Coastal engineering

ÖZ

CEM YÖNTEMİNE DAYALI BİR RÜZGAR DALGASI TAHMİN PROGRAMI

Polat, Emrecan
Yüksek Lisans, İnşaat Mühendisliği
Tez Yöneticisi: Prof. Dr. Ahmet Cevdet Yalçıner
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Mayıs 2022, 106 sayfa

Bu çalışmada, CEM Yöntemine dayalı rüzgar dalgası tahmini için bir hesaplama aracı sunulmaktadır. CEM yöntemi, fırtına ortalamalı rüzgar dalgası özelliklerinin hesaplanması için kullanılmaktadır. Bu hesaplama aracı ile CEM yöntemi, bir coğrafi konum için saatlik ortalama rüzgar hızı, yönü ve etkin kabarma uzunluğu verilerini kullanarak saatlik belirgin dalga yüksekliği, periyodu ve ortalama dalga yönü hesaplanmaktadır. Çalışmada, saatlik rüzgar dalgası özelliklerinin hesaplanmasında kullanılan tekil fırtınaların ve tekil fırtına sürelerinin belirlenmesine odaklanılmaktadır. Hesaplama aracı, Akdeniz`de rüzgar ve dalga şamandıra ölçümlerinin mevcut olduğu iki konuma uygulanmıştır. Tekil fırtınalar üç ana parametreye göre tanımlanır: minimum rüzgar hızı, maksimum saatlik rüzgar hızı değişimi ve maksimum saatlik rüzgar yönü değişimi. Çalışmada, bu parametreler için çeşitli aralıklar tanımlanmış ve bu parametrelerin değerlerinin fırtınaların belirlenmesine etkisi ve ortaya çıkan rüzgar dalgası özellikleri verilmiş ve tartışılmıştır. Ayrıca, saatlik rüzgar dalgası karakteristiklerinin hesaplanmasında çeşitli yaklaşımlar göz önünde bulundurulmaktadır. Bunlar kısaca şu şekilde sıralanmıştır; sürekli veri, kullanıcı tanımlı süre ile fırtına tabanlı ve fırtına süresi ile fırtına tabanlı. Bu yaklaşımlar için saatlik ortalama rüzgar dalgası özelliklerinin sonuçları, ilgili hata istatistikleriyle birlikte sunulmaktadır. En iyi yaklaşımın fırtına tabanlı kullanıcı tanımlı süre yaklaşımı olduğu görülmektedir. Çalışmada ele alınan lokasyonlar için kullanıcı tanımlı sürenin lokasyonun rüzgar iklimiyle ilişkili olduğu gözlemlenmiştir.

Anahtar Kelimeler: Dalga Tahmini, Parametrik Modelleme, Kıyı Mühendisliği

To my family,

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CHAPTER 1

INTRODUCTION

Forecasting wave parameters from measured wind parameters is an important phenomenon in the field of Coastal and Ocean Engineering. Design of coastal and offshore structures is dependent on the wave parameters which the structure will experience during its economic life. On the other hand, there are many meteorological stations all over the world but there are not so many buoys or stations for wave measurements. As a result of lack of wave measurement stations, estimations based on only historical wave measurements is not an option during design stage of many coastal and offshore structures and wind wave prediction methods must be utilized.

1.1 Scope

There are many methods to forecast wave parameters based on wind parameters. Although, there are several complex numerical models to do this forecast very accurately, most of the time, predictions from more simple, parametric methods prove to be satisfactory for engineering design purposes of coastal and offshore structures. The first studies to find a method to determine wave parameters from wind parameters started during World War II, to land troops on beaches of Europe (Kamphuis, 2000). The findings in these studies were reported and further studies in this area led to empirical parametric methods to determine wave parameters based on wind parameters. Some widely used parametric wave prediction methods are Pierson and Moskowitz (PM) method (Pierson and Moskowitz, 1964) SPM method (Shore Protection Manual Method) (US Army Corps of Engineers, 1984), Wilson method (Wilson, 1959), SMB method (Bretschneider, C.L., 1970), Jonswap Spectrum Method (Hasselmann et al., 1973), Donelan Method (Donelan, M.A., 1980) and CEM method (Coastal Engineering Manual) (US Army Corps of Engineers, 2000).

All the parametric wave prediction methods are empirical methods and basically, they are methods for forecasting wave height (H) and period (T) at a certain location, according to wind speed (U), fetch length (F) and duration of the storm (t). Other parameters like temperature and air pressure have an effect on wave generation but these parameters are neglected in simple parametric wave prediction models. It should also be noted that, definition of a storm is not accurately made for these parametric methods and selection of different storm parameters or values for these parameters lead to different results.

In this study, CEM Method was used to hindcast time-based wave parameters at locations where both wind and wave measurement stations exist. Then, hindcast wave data was compared with measured wave data. A computational tool was developed to make the work easier. So that, measured wind data and fetch length are given as input and the computational tool calculates wave parameters with selected parametric wave prediction models.

The computational tool uses three input values (U, F and t) for every single hour of calculations. Average wind speed (U) and fetch length (F) are averaged according to the storm duration (t). So, identifying the storm duration for every hour of calculation is one of the major focus points of this study. Three approaches to identify hourly storm durations are considered during development of the computational tool. These approaches are continuous data, storm-based with user defined duration and storm-based with storm duration. Moreover, to determine the storm duration a definition for storm is necessary. Minimum wind speed, maximum wind speed change and maximum wind direction change are three storm parameters used to define storms in this study. The computational tool was run multiple times with different approaches to identify hourly storm durations and with different values for the three storm parameters. The results are compared to measured wave data and results are reviewed and interpreted for different approaches of identifying hourly storm duration and different storm parameters.

It should be noted that, there are many similar studies to make time-based predictions using parametric wave prediction methods and the aim of this study is to make a similar study with an up-to-date programming language and determine best approach for identifying storm duration for hourly calculations and the best parameters to define storms.

1.2 Organization of the Thesis

This thesis is structured as 5 chapters. In chapter 1, an introduction to the topic is provided. Chapter 2 consists of literature review and detailed explanation of the current methods. In chapter 3, the algorithm of computational tool and different approaches considered during development of the computational tool are explained in detail. In chapter 4, results from application of computational tool to two datasets are shown and discussed and in chapter 5 thesis is summarized, and future studies are discussed.

CHAPTER 2

LITERATURE REVIEW

Forecasting wave parameters from measured wind parameters is an important phenomenon in the field of Coastal and Ocean Engineering. Design of coastal and offshore structures are dependent on the wave parameters which the structure will experience during its economic life. However, although there are many meteorological stations all over the world, there are not so many buoys or stations for wave measurements. As a result of lack of wave measurement stations, estimations based on only historical wave measurements may not be an option during design stage of many coastal and offshore structures and wind wave prediction methods must be utilized.

There are many methods to forecast wave parameters based on wind parameters. Although, there are many complex numerical methods to do this forecast very accurately, predictions from more simple, parametric methods prove to be satisfactory for engineering design purposes of coastal and offshore structures especially at the preliminary design stages with less cost and time. The first studies to find a method to determine wave parameters from wind parameters started during World War II, to land troops on beaches of Europe (Kamphuis, 2000). The findings in these studies were reported and further studies in this area led to empirical parametric methods to determine wave parameters based on wind parameters. Some widely used parametric wave prediction methods are Pierson and Moskowitz (PM Method) method (Pierson and Moskowitz, 1964), SPM method (Shore Protection Manual Method) (US Army Corps of Engineers, 1984), Wilson method (Wilson, 1959), SMB method (Bretschneider, 1970), Jonswap Spectrum

Method (Hasselmann et al., 1973), Donelan Method (Donelan, M.A., 1980) and CEM method (US Army Corps of Engineers, 2000).

All the parametric wave prediction methods are empirical methods and basically, they are methods for forecasting wave height (H) and period (T) at a certain location, according to wind speed (U), fetch length (F) and duration of the storm (t). Donelan's method also considers the wind and wave direction difference as an input parameter other than wind speed, fetch length and storm duration. Although, other parameters like temperature and air pressure also have an effect on wave generation, these parameters are neglected in simple parametric wave prediction models. These methods are used to predict the significant wave height and corresponding peak period of the waves which will be generated by a storm whose wind speed and duration are known. In other words, these methods predict a single significant wave height and peak period value for each storm. It should also be noted that, definition of a storm is not accurately made for these parametric methods and selection of different parameters or values for these parameters changes the resulting wave predictions. Review of studies using parametric wave prediction methods shows that selection of different storm parameters may be more accurate for different locations.

During design of coastal and offshore structures, forces which will be applied to the structure by the waves is an important design criteria. However, not only the forces by the waves but also the sediment transport and erosions and depositions on shorelines are a subject matter for coastal engineering studies. During such studies time-based long term wave predictions may be required for design purposes as waves generated by storms may create longshore currents which may effect the shorelines. However, above mentioned parametric wave prediction methods do not work on a time-based manner. Some studies have been conducted to use them in such a way. In this study some methods were proposed to use these parametric methods in a time-based manner. A computational tool was developed for calculations and results from the computational tool were compared to measured data to see the effectiveness and accuracy of proposed methods.

2.1 Definitions

2.1.1 Wind Speed

The wind blowing on the water surface creates a friction between air and water and due to this friction momentum of air is transferred to water. This transfer of momentum is the basic phenomenon which generates waves. The momentum transferred to the water body is directly related to wind speed. In fact, in most of the parametric wave prediction methods wave height is related with square of wind speed.

All parametric wave prediction methods studied use the wind speed at 10m elevation above water surface. However, wind measurements are not always done at 10m height. In fact, the measured wind speed data used were from a buoy which measures wind speed at 4m elevation above the water surface. There are some methods to predict wind speed at a certain elevation according to the wind speed at another elevation. Such a method was provided in Coastal Engineering Manual (US Army Corps of Engineers, 2003) as in Eq. 1 below.

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

Where U_{10} is the wind speed at 10m height in m/s, U_z is the measured wind speed in m/s and z is the elevation in m where wind speed was measured. This method was also proposed as a method to predict wind speed at 10m height in coastal engineering textbooks (Kamphuis, 2000). However, it is also mentioned in Coastal Engineering Manual that this method gives accurate results for measurements between 8m and 12m elevation above the water surface.

Another method was given by Bishop (1983) as shown in Eq.2 below.

$$U_z = U_{10}\left[1 + 0.0968 ln\left(\frac{z}{10}\right)\right] \qquad Eq. 2$$

where U_z is the measured wind speed in m/s, U_{10} is the wind speed at 10m height and z is the elevation in m where wind speed is measured.

In this study, since there was a note on Coastal Engineering Manual (US Army Corps of Engineers, 2003) about the method to be used for measurements at certain elevations the method described by Bishop (1983) was used. Although, it should also be noted that results from both methods were very close to each other would not have a significant impact on the error and accuracy calculations.

After calculating wind speed data at 10m elevation, average wind speed is calculated by simply getting arithmetic mean of wind speeds for the storm duration for which the calculation is made in parametric wave prediction methods.

2.1.2 Fetch Length

The measured data studied in the scope of this thesis is from buoys located in Eastern Mediterranean close to Antalya and Taşucu, Mersin. The buoys measure wind speed, wind direction, wave height and wave period. The geographical location of the buoys and wind directions are used to determine the fetch length. Fetch lengths of the buoys are determined for cardinal, intercardinal and secondary intercardinal directions on the map as shown on Figure 2-1 and Figure 2-2.

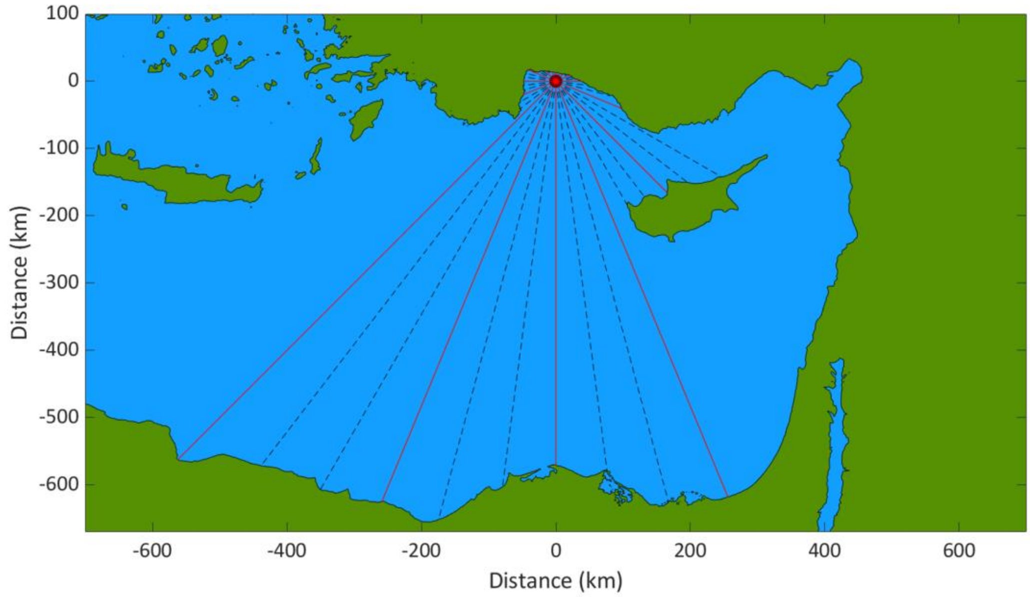

Figure 2-1 Fetch lengths for Antalya Bay

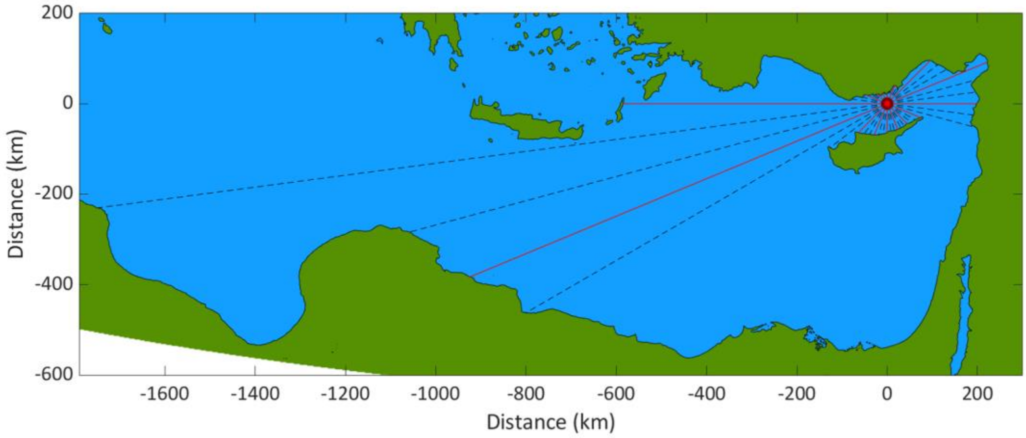

Figure 2-2 Fetch lengths for Taşucu, Mersin

The effective fetch lengths for both buoys are given on Table 2-1 below. As seen on Figure 2-1, Figure 2-2 and Table 2-1 both buoys are very close to the mainland on the north and the fetch lengths are limited in North directions. The fetch lengths for both buoys are less than 50km between Northwest and North-Northeast directions. Fetch lengths of Taşucu, Mersin buoy are also limited from the South by Cyprus Island. It can be seen on Table 2-1 that Antalya buoy has long fetches (>200km) for a ~90° angular interval, between Southwest and Southeast directions whereas Taşucu. Mersin buoy has long fetches (>200km) for only 45° angular interval between Southwest and West directions. Although, it should also be noted that Taşucu, Mersin buoy has the longest fetch with ~800km in the West-Southwest direction. The longest fetch for Antalya buoy is on South-southwest direction with ~650km.

Table 2-1 Effective Fetch Lengths for Antalya and Taşucu, Mersin

Direction	*Antalya (km)*	*Taşucu, Mersin (km)*
N	13.49	26.64
NNE	13.25	45.89
NE	16.22	109.57
ENE	23.13	176.26
E	48.10	182.79
ESE	144.48	121.16
SE	268.70	64.76
SSE	436.06	60.33
S	610.27	63.71
SSW	656.16	73.28
SW	429.66	323.26
WSW	146.78	792.69
W	46.83	646.57
WNW	36.04	115.37
NW	23.28	31.44
NNW	15.72	24.01

The fetch length used in the parametric wave prediction methods are calculated according to average wind directions of all the wind speed measurements for the duration of the storm. However, this average calculation cannot be done by simple summation and division because the average of two wind directions like 10° and 350° would result in 180° whereas it should have been 0°. In order to do this calculation all wind directions are considered as unit vectors and their sine and cosine values are averaged. Then arctangent of sine/cosine summations gives the average value. The equation used to calculate average wind direction is described in detail in equations 3, 4 and 5.

$$\theta = \begin{cases} \arctan\left(\bar{s}/\bar{c}\right) & \bar{s} > 0, \bar{c} > 0 \\ \arctan\left(\bar{s}/\bar{c}\right) + 180° & \bar{c} < 0 \\ \arctan\left(\bar{s}/\bar{c}\right) + 360° & \bar{s} < 0, \bar{c} > 0 \end{cases} \qquad Eq. 3$$

Where θ is in degrees,

$$\bar{s} = \frac{\sum_{i=1}^{n} \sin(\theta_i)}{n} \qquad Eq. 4$$

$$\bar{c} = \frac{\sum_{i=1}^{n} \cos(\theta_i)}{n} \qquad Eq. 5$$

Moreover, since wave height is related to square of wind speed in parametric wave prediction methods, weighted average of wind directions was used in this study (Koca, 1979). The method used to calculate weighted average of wind direction according to square of wind speed is described in equations 6, 7 and 8 below.

$$\theta_U = \begin{cases} \arctan\left(\overline{s_U}/\overline{c_U}\right) & \bar{s}_U > 0, \bar{c}_U > 0 \\ \arctan\left(\overline{s_U}/\overline{c_U}\right) + 180° & \bar{c}_U < 0 \\ \arctan\left(\overline{s_U}/\overline{c_U}\right) + 360° & \bar{s}_U < 0, \bar{c}_U > 0 \end{cases} \qquad Eq. 6$$

Where θ_U is weighted average of wind directions according to U_{10}^2, in degrees

$$\bar{s}_U = \frac{\sum_{i=1}^{n} U_i^2 \sin(\theta_i)}{\sum_{i=1}^{n} U_i^2} \qquad Eq.7$$

$$\bar{c}_U = \frac{\sum_{i=1}^{n} U_i^2 \cos(\theta_i)}{\sum_{i=1}^{n} U_i^2} \qquad Eq.8$$

After calculating the average wind direction, a simple interpolation is made to determine the corresponding fetch length.

2.1.3 Storm Duration

Storm duration is the total time a storm generates winds. Some conditions have been defined to determine if the measured wind speed data shall be considered a storm or not. These conditions are basically the conditions which determine if a storm has started if a storm is continuing and if a storm is ending. Basically, minimum wind speed, minimum storm duration, wind speed and direction changes and minimum calm durations are the conditions which determine the state of a storm.

The reviewed studies shows that these conditions were taken differently in numerous studies. Some studies define minimum wind speed as 4m/s whereas another study defines it as 3m/s. Some studies do not consider wind speed change as a storm ending condition whereas another study considers wind speed changes greater than 2.5m/s as a storm ending condition. In this study, calculations were performed according to different combinations of these conditions. In all the calculations minimum storm duration was considered to be 2 hours. So, 1 hour wind speeds greater than the selected minimum wind speed were not considered a storm.

Storm duration is actually the most important parameter for time-based calculations. Because, average wind speed and average fetch length at any hour are also determined according to the storm duration selected for that hour based on the selected storm conditions.

2.1.4 Fetch Limited, Duration Limited and Fully Developed Sea Conditions

In all parametric wave prediction methods generated wave height is proportional to wind speed, storm duration and fetch length. In other words, the height of the generated wave increases by increasing wind speed, storm duration and fetch length. However, there is a limit for wave height which can be generated by a certain wind speed. When storm duration and fetch length are long enough and does not limit the wave growth, the sea state reaches to fully developed sea state for the given wind speed which results in the maximum wave height that can be generated by that wind speed. Fully developed sea state condition is dependent on the wind speed only. For example, in CEM Method Eq.9 and Eq.10 below give the maximum significant wave height and peak period that can be reached by a certain wind speed even if the fetch length and storm duration are infinite.

$$\frac{gH_s}{U_*^2} = 211.5 \qquad Eq.9$$

$$\frac{gT_p}{U_*} = 239.8 \qquad Eq.10$$

Where H_s is in m, U_* is in m/s, T_p is in s and g is the gravitational acceleration in m/s^2. After H_s and T_p calculations are made in Coastal Engineering Manual method (CEM Method) a check is made to see if the calculated H_s or T_p are greater than the fully developed sea state condition H_s and T_p for the given wind speed. If so, H_s and T_p are taken as the values from the fully developed sea state conditions.

When wave generation is limited by short storm duration or fetch length the wave generation is defined as duration limited or fetch limited, respectively. These limits were defined in many parametric wave prediction methods. For example, CEM Method defines a minimum duration for given fetch length and wind speed values with Eq.11 below.

$$t_{min} = 77.23 \frac{F^{0.67}}{U_{10}^{0.34} g^{0.33}} \qquad Eq. 11$$

Where t_{min} is in s, F is in m, U_{10} is in m/s and g is the gravitational acceleration in m/s^2. If storm duration is less than t_{min} then the wave generation is limited by storm duration and it is the duration limited condition. In this case, an effective fetch length calculation is made and CEM Method is used with this effective fetch length. When storm duration is long enough for the given fetch length (i.e., storm duration is greater than t_{min}) then CEM Method calculations are made with geographical fetch lengths.

2.2 Parametric Wave Prediction Methods

Three parametric wave prediction models were reviewed within the scope of this study. Basically, these parametric methods use average wind speed, storm duration and fetch length as input and gives significant wave height and corresponding peak period as output. All parametric wave prediction methods reviewed are based on empirical studies and they use dimensionless parameters. The methods reviewed in this study are Wilson Method (Wilson, 1959), CEM Method (US Army Corps of Engineers, 2004) and Basic Jonswap Method (Hasselmann et al., 1973). These methods are described in detail in the following chapters.

2.2.1 Wilson Method

The minimum duration for waves to develop in a fetch limited case is given by Eq.12 below in Wilson Method.

$$t_{min} = F^{0.73} U_{10}^{-0.46} \qquad Eq. 12$$

If duration of the storm (t) is greater than the calculated minimum duration (t_{min}) then it is the fetch limited case and Eq. (13) and Eq. (14) below are used for calculating the significant wave height (H_s) and significant period (T_s). If storm duration (t) is less than the calculated minimum duration (t_{min}) then it is the duration limited case and effective fetch length (F_{eff}) is used instead of fetch length (F) in Eq. (13) and Eq. (14) below for calculating the significant wave height (H_s) and significant wave period (T_s). Effective fetch length is calculated with Eq. (12) above, replacing fetch length (F) with effective fetch length (F_{eff}) and using the minimum duration (t_{min}) which was calculated previously.

$$H_s = 0.3 \frac{U_{10}^2}{g} [1 - [1 + 0.004 \left(\frac{gF}{U_{10}^2}\right)^{\frac{1}{2}}]^{-2}] \qquad Eq. 13$$

$$T_s = 8.61 \frac{U_{10}}{g} [1 - [1 + 0.008 \left(\frac{gF}{U_{10}^2}\right)^{\frac{1}{3}}]^{-5}] \qquad Eq. 14$$

where; gravitational acceleration (g) is in m/s^2, fetch length (F) is in m, wind speed (U_{10}) is in m/s, storm duration (t) is in h, significant wave height (H_s) is in m, peak period (T_p) is in s.

The algorithm for Wilson Method is as shown in Figure 2-3

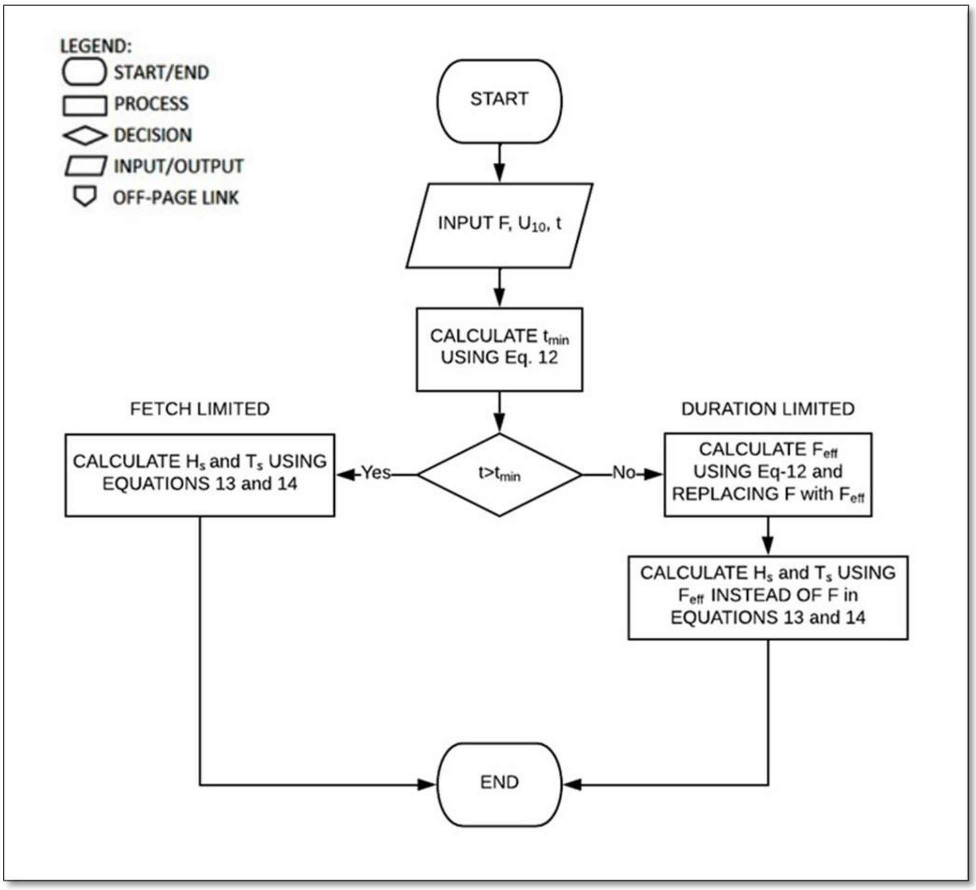

Figure 2-3 Algorithm flowchart for Wilson method

2.2.2 Coastal Engineering Manual (CEM) Method

The CEM Method uses friction velocity (U_*) instead of wind speed in the formulas. Friction velocity is calculated with a coefficient called the drag coefficient (C_D) which is obtained with Eq. 15 below as a function of wind speed at ten 10m height above the sea level (U_{10}). Then, the friction velocity (U_*) is calculated using Eq. 16 below, as a function of wind speed (U_{10}) and drag coefficient (C_D).

$$C_D = 0.001(1.1 + 0.035U_{10}) \qquad Eq. 15$$

$$C_D = \frac{U_*^2}{U_{10}^2} \qquad Eq. 16$$

It is decided whether the condition is duration or fetch limited with the calculation of minimum duration (t_{min}), which is defined as a function of wind speed (U_{10}) and fetch length (F) in Eq. 17 below. If storm duration (t) is greater than minimum duration (t_{min}) it is the fetch limited condition. Otherwise, it is the duration limited condition.

$$t_{min} = 77.23 \frac{F^{0.67}}{U_{10}^{0.34} g^{0.33}} \qquad Eq. 17$$

In the duration limited case an effective fetch length (F_{eff}) is calculated as a function of storm duration (t) and friction velocity (U_*) with Eq. 18 below.

$$\frac{gF_{eff}}{U_*^2} = 5.23x10^{-3} \left(\frac{gt}{U_*}\right)^{\frac{3}{2}} \qquad Eq. 18$$

Eq. 19 and 20 below are used to calculate significant wave height and peak period (T_p) in CEM Method. In duration limited cases effective fetch length (F_{eff}) shall be used instead of fetch length (F) in Eq. 19 and Eq. 20.

$$\frac{gH_s}{U_*^2} = 4.13x10^{-2} \left(\frac{gF}{U_*^2}\right)^{\frac{1}{2}} \qquad Eq. 19$$

$$\frac{gT_p}{U_*} = 0.651 \left(\frac{gF}{U_*^2}\right)^{\frac{1}{3}} \qquad Eq. 20$$

Fully developed sea conditions are defined as a function of friction velocity (U_*) in CEM Method with Eq. 21 and Eq. 22 below. These values are the maximum values of significant wave height (H_s) and peak period (T_p) for a given friction velocity (U_*). It should be checked if wave height (H_s) and peak period (T_p) values calculated with Eq. 19 and Eq. 20 are greater than the values calculated from Eq. 21 and Eq. 22. If so, it is a fully developed sea condition and values from Eq. 21 and Eq. 22 are the significant wave height and peak period.

$$\frac{gH_s}{U_*^2} = 211.5 \qquad Eq.21$$

$$\frac{gT_p}{U_*} = 239.8 \qquad Eq.22$$

where; gravitational acceleration (g) is in m/s^2, fetch length (F) is in m, wind speed (U_{10}) is in m/s, storm duration (t) is in s, significant wave height (H_s) is in m, peak period (T_p) is in s, The algorithm for CEM method is shown in Figure 2-4.

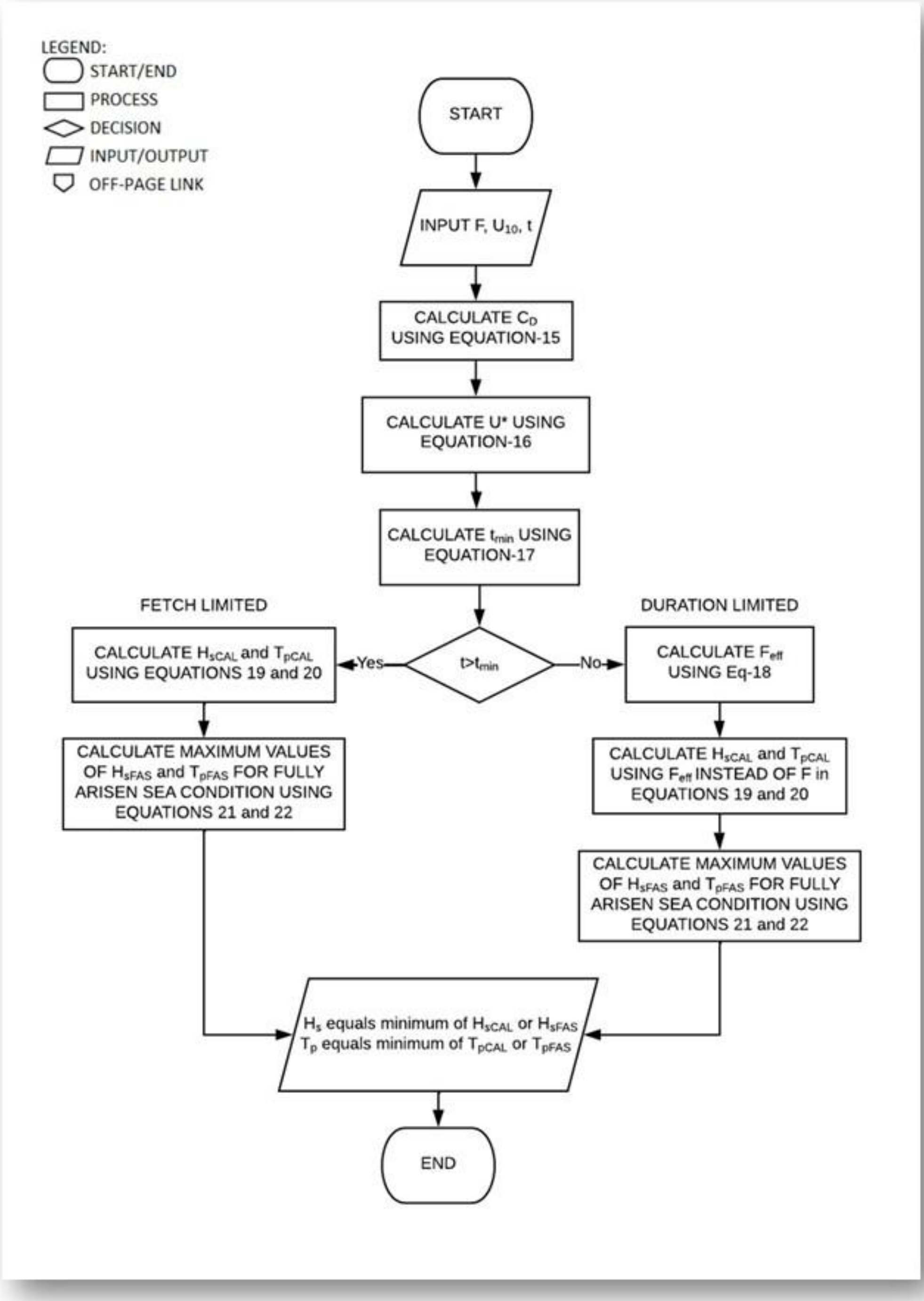

Figure 2-4 Algorithm for CEM Method

2.2.3 Basic Jonswap Method

Basic Jonswap Method (Hasselmann et al.,1973) defines dimensionless parameters for wave hindcasting from storm data. These dimensionless parameters are defined in Eq. (23), Eq. (24), Eq. (25), Eq. (26).

$$F^* = \frac{gF}{U^2} \qquad Eq. 23$$

$$H_{m0}^* = \frac{gH_{m0}}{U^2} \qquad Eq. 24$$

$$T_p^* = \frac{gT_p}{U} \qquad Eq. 25$$

$$t^* = \frac{gt}{U} \qquad Eq. 26$$

Relations between these dimensionless parameters are in Eq. (27), Eq. (28), Eq. (29).

$$H_{m0}^* = 0.0016(F^*)^{\frac{1}{2}} \qquad Eq. 27$$

$$T_p^* = 0.286(F^*)^{\frac{1}{3}} \qquad Eq. 28$$

$$t^* = 68.8(F^*)^{\frac{2}{3}} \qquad Eq. 29$$

Replacing these equations to obtain equations for significant wave height and peak period, we get Eq. (30) and Eq. (31).

$$H_{m0} = \frac{0.0016UF^{\frac{1}{2}}}{g^{1/2}} \qquad Eq. 30$$

$$T_p = \frac{0.286U^{\frac{1}{3}}F^{\frac{1}{3}}}{g^{2/3}} \qquad Eq. 31$$

In the fetch limited condition equations Eq. 30 and Eq. 31 can be used with measured wind speed and fetch length. However, in duration limited case an effective fetch length is calculated. Fetch length is replaced with effective fetch length in Eq. 30 and Eq. 31. In order to calculate effective fetch length, F* in Eq. 29 is replaced with F_{eff}*. If F*<F_{eff}* then the storm is fetch limited. Otherwise, it is duration limited.

Fully arisen sea conditions are determined with values of the dimensionless parameters as below. If any of these dimensionless values are greater than the below values, significant wave height and peak period shall be determined according to below equations

$$H_{m0}^* = 0.243;\ T_p^* = 8.13; \quad t^* = 71500 \qquad Eq.32$$

where, gravitational acceleration (g) is in m/s^2, fetch length (F) is in m, wind speed (U_{10}) is in m/s, storm duration (t) is in s, significant wave height (H_s) is in m, peak period (T_p) is in s. The algorithm for Basic Jonswap Method is shown on Figure 2-5.

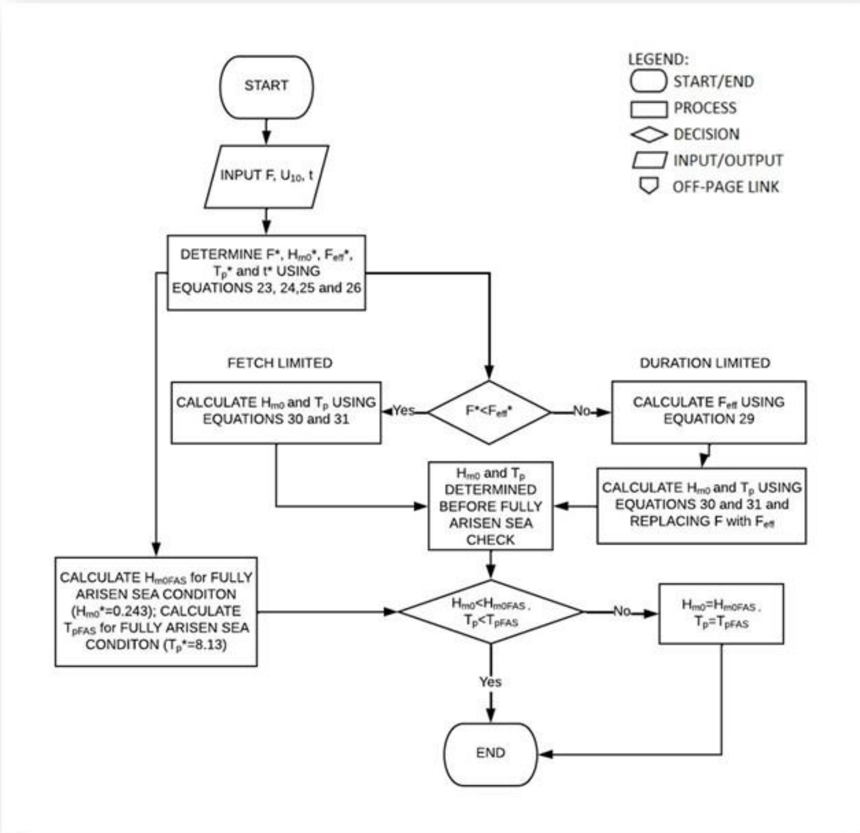

Figure 2-5 Algorithm for Basic Jonswap Method

2.3 Time-Based Parametric Wave Prediction Models

As mentioned in Chapter 1.1, there are some methods proposed for using parametric methods in a time-based manner. These methods have been reviewed in detail during this study. Some of the reviewed methods are discussed below in detail.

One of the methods proposed by Kamphuis (2000) calculates wave parameters for consecutive segments of time during a storm with Basic Jonswap Method described in Chapter 2.2.3. In the Kamphuis' method when a storm starts, the calculations are made with the Basic Jonswap Method for the first segment of time (t_i) and wave parameters (H_i and T_i) are obtained for this segment of time. For the second segment of time, since the energy of the wind is added to the existing energy of the wave, and since energy is closely related to wave height, it is suggested that the wave height of previous time segment (H_i) may be translated into extra storm duration for the next time segment. In order to do that the H^*_{i+1}value is calculated using previously calculated H_i and the average wind speed of the next hour with Equation 33 below.

$$H^*_{i+1} = \frac{gH_i}{U^2_{i+1}} \qquad Eq. 33$$

Then using Eq.29 and Eq.30 H^*_{i+1} is translated into a dimensionless time value (t^*_2) and (t^*_j) may be translated into a time value (t_j) using Eq. 26. The calculated extra time is added to the second time segment to obtain (t_{i+1}). Then Basic Jonswap Method calculations are made with t_{i+1} and U_{i+1} to calculate H_{i+1} and T_{i+1}. Then the method is repeated until the end of the storm to obtain time based wave parameters.

There are also other studies using the energy add on principle (Özhan E., 1977). The study by Özhan (1977) proved to give consistent time-based results when compared with wave measurements. The study considered wind, in the prevailing wind direction of the location only and when wind direction changed, vectoral component of the wind in the prevailing wind direction was used as the wind speed value for the calculations, which was a different approach than other studies reviewed. It should be noted that when the wind speeds are considered from a single direction, fetch length also remains constant for all the time intervals for which the calculations were carried out.

Another similar study defines storm conditions, divides the storms into time segments and performs calculations with parametric wave prediction methods for these time segments (Akpınar et al., 2014).

Also, there are other similar studies reviewed which work with similar principles but defines different storm conditions. All these studies require a definition for a storm. For example, some studies suggests when wind direction changes more than

15° the storm ends and another storm starts(Akpınar et al., 2014), whereas other studies suggest this value to be 90° (Şahin et al., 2007). Another study suggests a 2 hour minimum duration for the minimum wind speed to be considered a storm (Koca, 1979).

In this study, the developed computational tool first determines storms and then calculates wave parameters for hourly segments of the storms. The developed computational tool allows the user to input different storm conditions and do calculations based on different storm conditions. Also, three concepts for defining storm duration at every time segment were proposed. These concepts are continuous data, storm-based with user-defined duration and storm-based with storm duration. In the continuous data concept, a time window is determined by the user and the computational tool do calculations at every time segment as if there has been a storm with a storm duration of the determined time window value. In the storm-based concepts, first all data is reviewed to determine storms. Storm start and ending hours are determined and the computational tool does calculations only for the storms. At the first hour of the storm the storm duration is taken as 1 hour, and 2 for the second hour and so on. In the user-defined duration concept the time window value becomes the maximum storm duration value. The logic behind this idea is that, even if a storm lasts for a very long time, the effects of the wind speeds long hours ago may not have a significant effect on the current wave height. So, user defines this time window value, and this time window value becomes the maximum time interval that the calculations are made for every storm. If storm-based with storm duration concept is selected the time window concept is not considered and computational tool does the calculations with increasing storm duration at every hour up to the end of the storm. In both storm-based concepts computational tool continues to do calculations and give results for decay of the waves after storm ends. In storm-based, user-defined duration concept calculations after storm ends are made considering the storm duration equals time window and, in the storm-based with duration concept calculations after storm ends are made with the storm duration.

CHAPTER 3

ALGORITHM FOR TIME-BASED ESTIMATION

Although all the parametric methods were developed for estimating single values for wave height and wave period, they can be used to obtain time-based estimations of wave height and period by simply using the storm data of certain time intervals separately for the estimations. In other words, if there is one wind speed measurement for every hour of a storm, the first hour of a storm may be considered as a separate storm and wave parameters may be estimated for the first hour, for the second wind speed measurement, the storm shall be considered as a two-hour storm with an average wind speed of first and second measurements and so on.

In this study the first method to turn parametric wave prediction methods to time-based calculation methods was based on a constant time window method independent from the storm conditions. In other words, if the time window is selected as 10 hours, the computational tool considers storm duration as 10 hours, determines the average wind speed and fetch length for the previous 10 hours' data and then makes the calculations. If the resulting significant wave height is less than 0.5m then this result is neglected. Actually, this neglection somehow may be considered as introducing a storm condition into the calculations. Because, the computational tool works as if there is no storm condition if the generated wave height is less than 0.5m and otherwise the weather state is considered a storm condition. This method will be referred as Continuous Data.

The other methods used to turn the parametric wave prediction methods to time-based calculation methods are based on storm conditions. These methods also use time window concept. Two methods were used in the studies. One of them uses a constant time window and the other method uses storm duration of every individual storm as the time window for calculations of that storm. These methods will be referred as “storm-based with user-defined duration” and “storm-based with storm duration”. In order to include storm variables into the calculations, a definition for “storm“ which can be determined based on predefined storm conditions is required. After defining storm conditions, the meteorological data may be separated into storms and calm hours and then the calculations may be performed. There are many different definitions for storms in different studies based on storm conditions like minimum wind speed (U_{min}), minimum storm duration, maximum wind speed change (ΔU) and maximum wind direction change ($\Delta\Theta$). Storm conditions which are used to define a storm and parameters of these storms which are used in parametric wave prediction methods are described in detail in the chapters below.

3.1 Time Window Concept

The main purpose of the developed computational tool is to use parametric wave prediction methods in a time-based way. For this purpose, three concepts to identify hourly storm durations have been introduced. These concepts are referred to as time window concepts and the maximum storm duration to be used in the computational tool is referred to as time window. Time window concept is used in three different ways based on the consideration of storm conditions or not and time window being user-defined or not. These three concepts are described in detail in the chapters below.

3.1.1 Continuous Data

In the first method storm conditions are not considered. Storm duration is always equal to user-defined time window value. Average wind speed and fetch length are determined according to the previous data within the duration of the storm and then the calculations are made using the parametric wave prediction methods. This time window concept was called “continuous data”. As seen in Figure 3-1 in continuous data concept storm conditions are not considered and computational tool does not define the storms before running for parametric wave prediction methods. At every hour the computational tool considers the storm duration as the predefined time window and calculates the average wind speed and fetch length as if there has been a storm of time window duration. However, the outputs of the calculated significant wave heights less than 0.5m are not considered as outputs by the computational tool. So, somehow it may be considered that the computational tool considers H_s>0.5m as a storm condition.

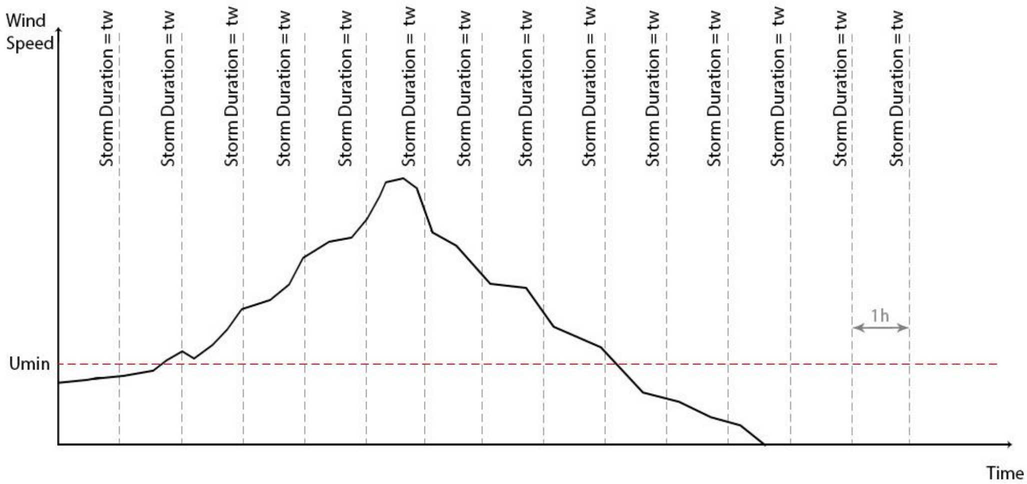

Figure 3-1 Continuous Data Concept

3.1.2 Storm-Based with User-Defined Duration

In storm based models, calculations start at the storm start point with 1 hour storm duration then calculation is made at the second hour of the storm with two hours storm duration and storm duration increases up to the user-defined time window. In this Storm-Based with User-Defined Duration method user-defined time window is an upper limit for the storm duration. When storm duration reaches the selected time window value, calculations are made considering storm duration is equal to the time window for the next hour data and all remaining future data of the storm. When a storm finishes according to the predefined storm conditions (for example with the conditions wind speed lower than U_{min} or hourly wind direction change is greater than $\Delta\Theta$) the computational tool continues to calculate wave heights until wave height is less than 0.5m. Because, when a storm ends the height of generated waves may continue to stay at certain levels for some more hours. This concept is defined in detail in Figure 3-2 below.

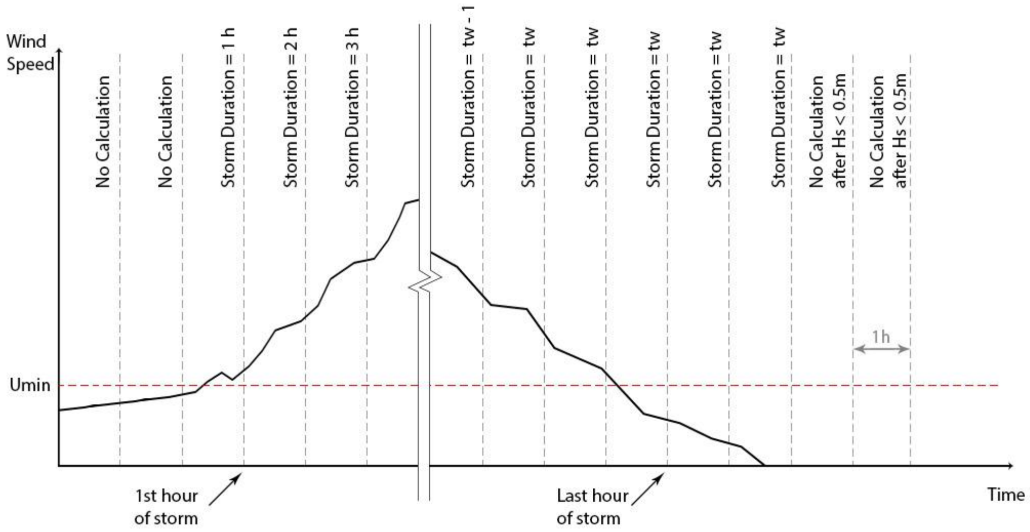

Figure 3-2 Storm-Based with User-Defined Duration Concept

3.1.3 Storm-Based with Storm Duration

The Storm-Based with Storm Duration method uses the same system as Storm-Based with User-Defined Duration method except for time window being a variable value according to the storm for which the calculations are made. When calculations for a storm starts, time window is taken equal to the total storm duration of the storm and calculations continue up to the end of the storm by increasing storm duration value at every hour until the end of the storm. When storm ends calculations continue to be made with total storm duration until wave height is less than 0.5m.

As seen in Figure 3-3 when the weather condition is not a storm according to predefined storm conditions the computational tool does not do any calculations. When storm starts, computational tool starts doing calculations after the first hour considering the storm duration is 1h. Then in the following hours computational tool does the calculations increasing the storm duration one hour for every hour up to the determined total storm duration which is equal to the time window. After storm ends computational tool continues to do calculations with storm duration equal to time window which is the total storm duration of recent storm until H_s>0.5m.

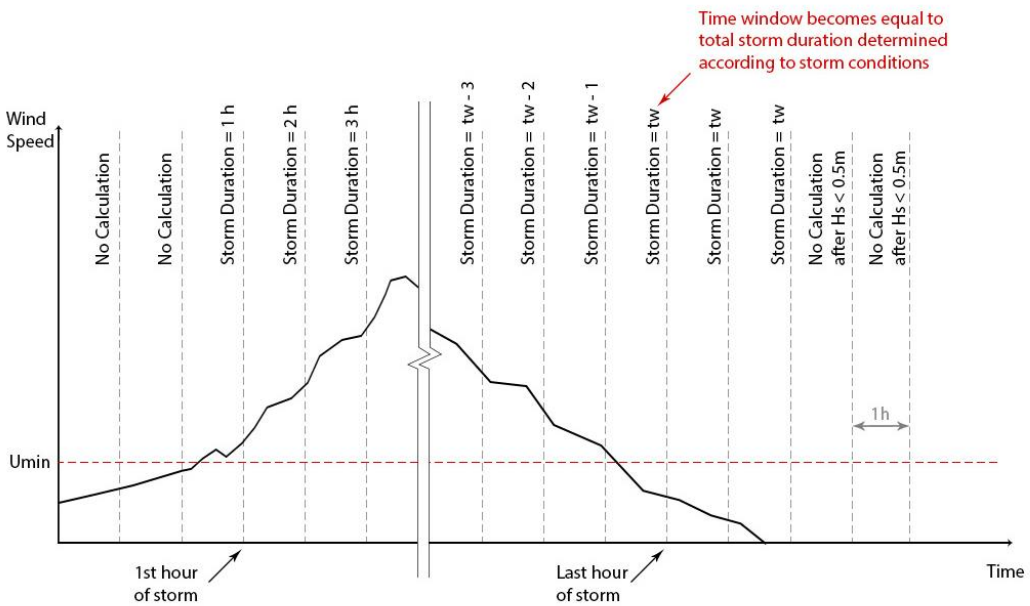

Figure 3-3 Storm-Based with Storm Duration Concept

3.2 Storm Conditions

3.2.1 Minimum Storm Duration and Minimum Generated Wave Height

Considering wave generation characteristics of storms, a minimum duration of 2 hours and minimum generated wave height of 0.5m was used and 1 hour duration storms and wave heights less than 0.5m were not considered as storms during this study (Koca, 1979). During calculations, first all data satisfying the predefined storm conditions are marked as storm start, storm continuation or storm end data. Then, properties of the storms are determined. One of properties determined is the storm duration. After storm properties are determined one-hour storms are deleted. The developed computational tool does not allow the user to change these two storm conditions (i.e. minimum storm duration and minimum generated wave height) but all other storm conditions described below are determined by the user before running the computational tool.

3.2.2 Minimum Wind Speed (U_{min})

Minimum wind speed is the most important parameter to define a storm. Basically, all the values greater than a pre-defined minimum wind speed are considered a storm if other storm criteria are also satisfied. In this study many trials have been made with different minimum wind speed conditions. Many studies use different minimum wind speeds as a storm condition. In this study it was seen that different selected minimum wind speed conditions change the accuracy of calculated wave measurements. So that the developed computational tool was designed to allow the user to define minimum wind speed condition and make calculations accordingly.

Minimum wind speed is the first storm condition for which the developed computational tool starts defining storms. First all wind data which has a speed greater than the minimum predefined wind speed condition are marked. Then consecutive data are checked for other storm conditions.

3.2.3 Change of Wind Direction ($\Delta\Theta$)

Change of wind direction may be considered as a storm ending condition. When wind direction changes with a value greater than the predefined maximum wind direction change ($\Delta\Theta$), even if the minimum wind speed does not decrease to a value smaller than minimum wind speed condition, it is considered that wave directions also change, and the computational tool starts to do calculations as if a new storm has started. When the direction of waves changes their momentum and energy do not add up and waves from the previous storm are considered as swell waves. This is a reasonable method to determine ending and starting hour of storms. In fact, World Meteorology Organization's Guide to Wave Analysis and Forecasting states when wind direction changes more than 30° wave directions are assumed to be aligned with the new direction and when wind direction changes greater than 30°, existing waves shall be considered swell waves and newly generated waves shall be computed with new wind direction (WMO, 1998). This phenomenon has also been discussed in similar studies and different $\Delta\Theta$ value were shown to give better results, compared to measured wave data, when used with parametric wave prediction methods (Şahin et al., 2007).

In this study, computational tool was run for different maximum wind direction change values and their results were reported as well. The computational tool runs based on hourly wind direction change values.

3.2.4 Change of Wind Speed (ΔU)

Change of wind speed is another criteria to determine the ending and starting hour of a storm. A maximum wind speed change is defined for storms and when wind speed change is above the predefined maximum wind speed change, even if the wind speed at the next hour is not below the minimum storm wind speed, the storm is considered to be finished and another storm is considered to be started. In this study change of wind speed was considered as a storm condition and calculated-measured wave height values were compared for different values of maximum wind speed change condition. However, it should also be noted that when wind directions of consecutive hours remain in a certain interval, wave directions also remain in a certain interval. This results in accumulation of wave energy. In some studies, maximum wind speed change condition was not considered as a storm condition and minimum error was obtained without the use of maximum wind speed change condition (Sahin et al., 2007). This option was also considered within the scope of this study and it should be noted hourly wind speed change values were used in the scope of this study.

3.2.5 Consecutive Storms

There are similar studies using parametric wave prediction methods for time-based predictions which consider the effect of consecutive storms. When two consecutive storms with similar wind directions and a short period of time between them occur, the energy from the second storm may add up to the existing energy remaining from the first storm. This phenomenon was considered in some similar studies. However, in this study this effect of consecutive storms was not taken into consideration. This study focuses on finding best storm duration concept and best storm conditions to predict wave height with minimum errors. Even if the direction of consecutive storms are similar and there is a short period of time between them, the computational tool starts calculations of second storm as if the existing waves generated by the first storm are swell waves. So that, at the first hour of the second storm, storm duration is taken as 1 hour and calculations are made with 1 hour storm duration and corresponding wind speed and fetch length.

3.3 Inputs of the Computational Tool

The computational tool developed for this study was developed to be used for wind and wave data from two buoys located around the coastline of Turkey. Time resolution of wind data from these buoys was 1 hour and time resolution of wave data was 30 minutes. The computational tool was designed to work with the data which has the same time resolution (i.e. 1 hour for wind speed and 30 minutes for wave height). Although, it should also be noted that, since wind data resolution is 1 hour, output significant wave height calculations from the computational tool also have a 1 hour resolution. When a comparison between measured and calculated wind data is made the time resolution of this comparison will be 1 hour and the computational tool will take the larger value of measured significant wave height from the two measurements for every hour. Of course, input of wave measurements is not mandatory and it is only needed if a comparison between calculated and measured wave heights will be made.

Other than wind and wave data, fetch lengths of the location storm conditions, time window concept, time window value and desired parametric wave prediction methods shall be input to the computational tool. Fetch lengths of the location towards all cardinal, intercardinal and secondary intercardinal directions shall be input to the computational tool (with 22.5° intervals). The user shall select one of the three time window concepts, input the desired time window value and also input desired storm conditions (U_{min}, ΔU and $\Delta\Theta$). If the Continuous Data concept is selected storm conditions will not be considered. In other time window concepts the computational tool will first determine storms and their properties and then do the calculations with parametric wave prediction methods for significant wave height and peak period. In Storm-Based with Storm Duration concept, time window value is not required and if a value is input in the textbox this value will be ignored. The computational tool will do calculations with all or any of the parametric wave prediction methods selected.

The computational tool was coded in Visual Basic and works on a Microsoft Excel file. A user interface was created to input desired time window concept, time window value, storm conditions and parametric wave prediction methods and this user interface shall be used to input these values.

Format and method for data input is described in chapters below in more detail.

3.3.1 Wind Data Input

The computational tool was developed based on buoy readings in Turkey and input format for the computational tool was designed according to data format of these buoys. Wave data shall be input in a worksheet named “ruzgar”. Data shall be in the form of 6 columns: year, month, day, hour, average wind direction and average wind speed, respectively. The first row was dedicated for headings for each column. So, data shall start from the second row. Starting from the second-row, data for each column shall be input as described below:

1st column: Year, 4 digits integer numeric value

2nd column: Month, 1 digit or 2 digits integer numeric value

3rd column: Day, 1 digit or 2 digits integer numeric value

4th column: Hour, 1 or two digits integer numeric value between 0 and 23

5th column: Azimuth wind direction, 1 to 3 digits integer numeric value between 0° and 360°.

6th column: Wind speed, numeric value with 1 decimal value in m/s

Data shall be input in an increasing order according to date and time. There may be date and hour gaps between the data if there is missing data. However, even if there are gaps in the data, it has to be ordered according to increasing date and hour without any empty rows. An example of wind data input is shown in Table 3-1.

Table 3-1 Wind Data Input Example

	A	B	C	D	E	F
1	Year	Month	Day	Hour	Average Direction	Average Wind Speed
2	2015	3	24	21	254	0.2
3	2015	3	24	22	258	0.3
4	2015	3	24	23	142	0.1
5	2015	3	25	0	246	0.3
6	2015	3	25	1	209	0.1
7	2015	3	25	2	260	0.3
8	2015	3	25	3	286	0.1
9	2015	3	25	4		
10	2015	3	25	5		
11	2015	3	25	6		
12	2015	3	25	7		
13	2015	3	25	8		
14	2015	3	25	9	236	0.2
15	2015	3	25	10	231	0.2
16	2015	3	25	11	314	0.1
17	2015	3	25	12	294	0.7
18	2015	3	25	13	9	0.3
19	2015	3	25	14	260	2.7

ruzgar | dalga | Chart1 | Calculations

3.3.2 Wave Data Input

If wave hindcasting will be done and measured values will be compared with computed values, then measured wave data shall be input to the computational tool. The original buoy readings, which were used during computational tool development stage had a time resolution of 30 minutes. So, it had two significant wave height (H_s) and peak period (T_p) values for each hour and the software was developed to use wave input in this format. Wave measurement data must be input in 7 columns into worksheet named “dalga”. The first five columns are for date, hour and minute. Other two columns are for measured H_s and T_p. Data must be in increasing order of time without any empty rows. Also, the dates and times in measured wave data should be a subset of measured wind data. In other words, the date & time of starting data for wave measurements should be greater than or equal to the date & time of starting data for wind measurements and date & time of ending data for wave measurements should be less than or equal to date & time of ending data for wind measurements. The first row of the worksheet is for headings. So, data shall be input starting from the second row. The values in the columns shall be as below:

1st column: Year, 4 digits integer numeric value

2nd column: Month, 1 digit or 2 digits integer numeric value

3rd column: Day, 1 digit or 2 digits integer numeric value

4th column: Hour, 1 or two digits integer numeric value between 0 and 23

5th column: Minute, 1 digit or 2 digits numeric value

6th column: Significant wave height (H_s), numeric value with two decimal places in m

7th column: Peak period (T_p), numeric value with one decimal place in s

An example of wave data input is shown in Table 3-2 below.

Table 3-2 Wave Data Input

	A	B	C	D	E	F	G
1	Year	Month	Day	Hour	Minute	Hs	Tp
2	2015	3	24	13	30	0.00	13.0
3	2015	3	24	15	0	0.02	10.6
4	2015	3	24	15	30	0.44	10.8
5	2015	3	24	16	0	0.22	11.1
6	2015	3	24	16	30	0.13	11.8
7	2015	3	24	17	0	0.79	11.4
8	2015	3	24	17	30	0.14	11.0
9	2015	3	24	18	0	0.78	11.5
10	2015	3	24	18	30	0.93	10.9
11	2015	3	24	19	0	0.80	11.5
12	2015	3	24	19	30	0.01	10.1
13	2015	3	24	20	0	0.57	11.1
14	2015	3	24	20	30	0.84	11.3
15	2015	3	24	21	0	0.74	11.7
16	2015	3	24	21	30	1.05	12.0
17	2015	3	24	22	0	1.01	11.8
18	2015	3	24	22	30	1.25	11.7

ruzgar | dalga | Chart1 | Calculations | firtinalar | Hi:

3.3.3 Fetch Length Data Input

For the fetch data, directions in both degrees and text format and corresponding effective fetch lengths in kilometers shall be entered into a separate worksheet named “fetch”. The first row is for headings and data shall be input starting from the second row. Data in each column shall be as below:

> 1st column: Cardinal, intercardinal and secondary intercardinal directions, numeric value with one decimal. The values should be 0, 22.5, 45, 67.5, 90, 112.5, 135, 157.5, 180, 202.5, 225, 247.5, 270, 292.5, 315, 337.5. Values shall be ordered in an increasing order.

2nd column: Cardinal, intercardinal and secondary intercardinal directions, 1 to 3 alphabetic values. The values should be N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW. These values should be in the correct order and rows with corresponding values in the 1st column.

3rd column: Effective fetch lengths, numeric value with decimal places as required in km

An example of fetch length data input is shown in Table 3-3 below.

Table 3-3 Fetch Length Data Input

	A	B	C
1		Direction	Effective Fetch
2	67.5	'ENE'	23.12609758
3	45	'NE'	16.21874367
4	22.5	'NNE'	13.25409696
5	0	'N'	13.48924213
6	337.5	'NNW'	15.72377494
7	315	'NW'	23.2826814
8	292.5	'WNW'	36.04352693
9	270	'W'	46.83094168
10	247.5	'WSW'	146.7805367
11	225	'SW'	429.6646511
12	202.5	SSW'	656.158382
13	180	'S'	610.2673797
14	157.5	'SSE'	436.0593741
15	135	'SE'	268.7012836
16	112.5	'ESE'	144.4833376
17	90	'E'	48.10144565

OPEN USER INPUT FORM

ruzgar | dalga | fetch | Chart1 | Calculations | firtina

A button was put on the worksheet “fetch” to start the computational tool. After finishing all the inputs this button named “Open User Input Form” shall be clicked to start the computational tool by opening the user interface.

3.3.4 Time Window and Storm Conditions Input

After wind, wave and fetch length data are input on the worksheets and the button on worksheet “fetch” is clicked a user interface is opened as seen on Figure 3-4 below. On this user interface the user shall select a time window value on the time window text box at the top. Then select the parametric wave prediction methods to make the calculations. One, two or all of the parametric methods may be selected and the computational tool will do the calculations and give outputs according to all selected parametric wave prediction methods. Time window concept shall be selected on this user interface and storm conditions shall also be input on this user interface. After finishing the input of desired conditions for the calculations when “RUN” button is clicked. The computational tool starts processing and preparing the outputs.

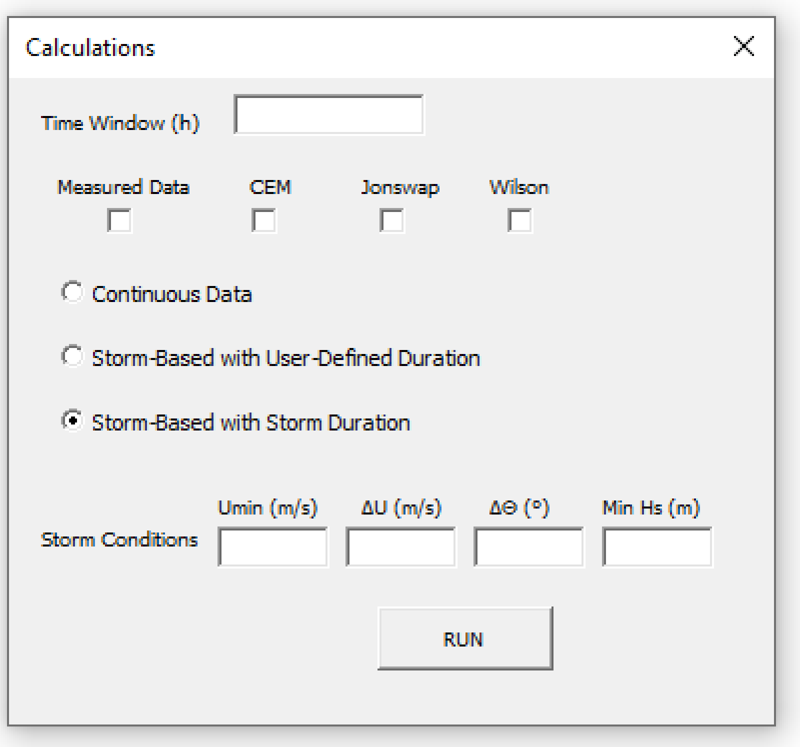

Figure 3-4 User Interface

3.4 Algorithm of the Computational Tool

After all data, time window concept and storm conditions are input the computational tool and it is run it first creates the dates from the starting hour to the ending hour of wind data and writes the corresponding wind data and wave data on another sheet. So that, no change is made on the original input data. Also, the input data does not have the dates and times for missing data. In the new worksheet the computational tool first writes all the dates and times between the starting and ending hour of wind data and leaves the wind and wave data empty on dates and times with missing data. So, that the requirement for checking date and time at every consecutive step is not required anymore and it is known that the data is increasing one hour at every step.

After data is taken to the new worksheet with the new format the computational tool first runs for determining storms, then runs for parametric wave prediction method calculations and then for creating outputs. The algorithms are defined in detail below.

3.4.1 Algorithm for Determining Storms

If selected time window concept is storm-based the computational tool first runs for determining the storms and creating a table for storm properties. If continuous data concept is selected storms are not determined and the computational tool directly runs for time-based parametric wave prediction.

When computational tool starts determining storms it first checks the wind speed and if the wind speed is greater than user defined minimum storm wind speed then it marks this data as a storm data. Then it checks previous data and if the previous data is not a storm data it marks this data as a “storm start” data. Otherwise, if the previous data is a storm data too then it marks the data as a “storm continuation” data. Then the computational tool checks for the other two storm conditions wind speed change and wind direction change. If any of these conditions change more than pre-defined storm condition values (ΔU and $\Delta\Theta$) the wind data is marked as a "storm ending" data. If the wind speed of next data is less than U_{min} the data is marked as "storm ending" data as well. The algorithm is defined in detail in Figure 3-5 below.

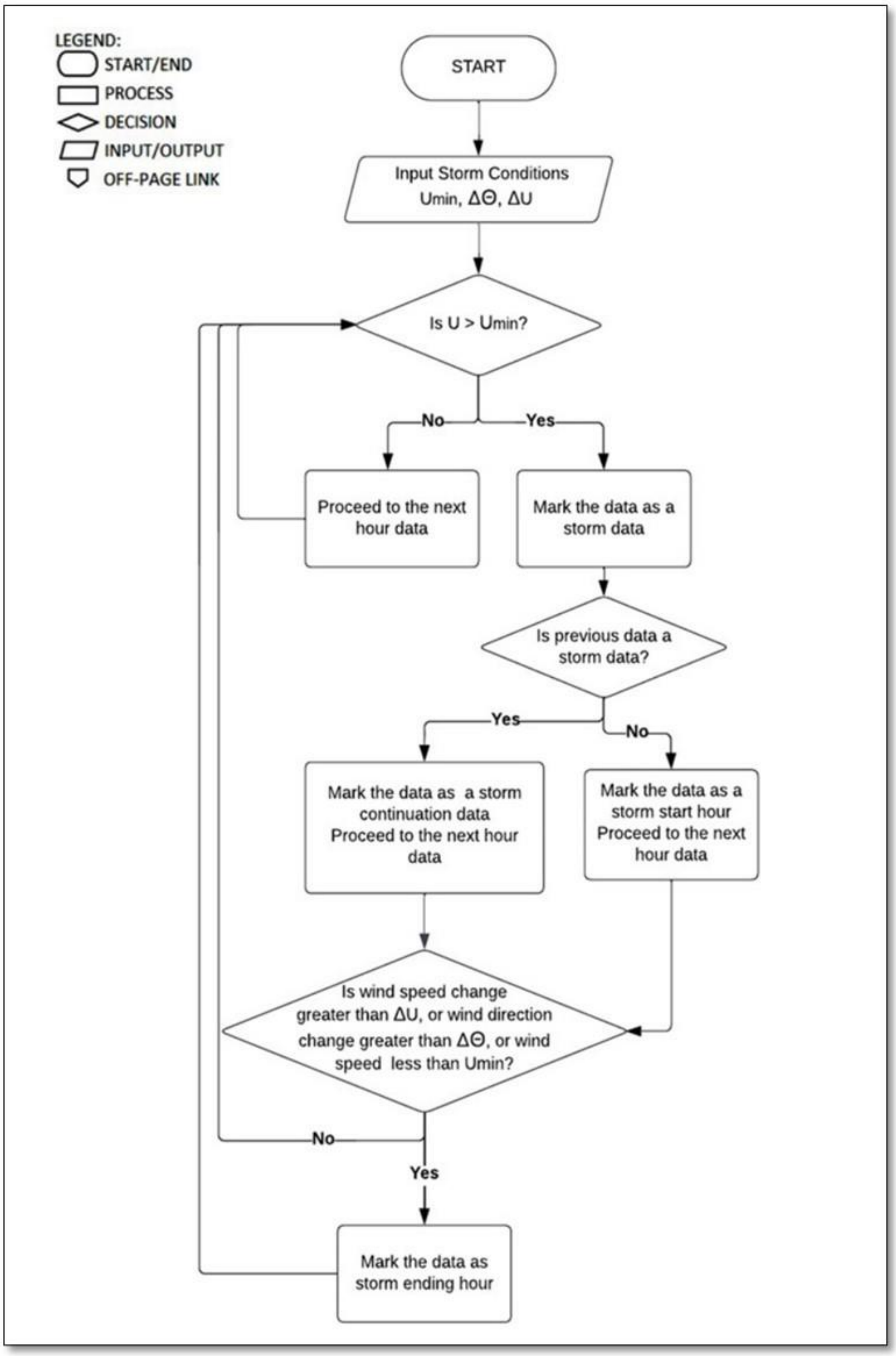

Figure 3-5 Algorithm for Determining Storms

So, basically after this algorithm is run all the data (i.e., every hour step) is being marked as “no storm”, “storm start”, “storm continuation” or “storm ending” data. Then a unique storm name is given at the “storm start” data starting from “Storm-

1” to “Storm-n”. Another condition for storms is the minimum storm duration which is 2 hours. In order to apply this condition the computational tool checks all the storms and deletes all the storms with one hour duration and then renames all the storms from “Storm-1” to “Storm-n” again. The algorithm flowchart for the minimum storm duration condition is shown in Figure 3-6 below.

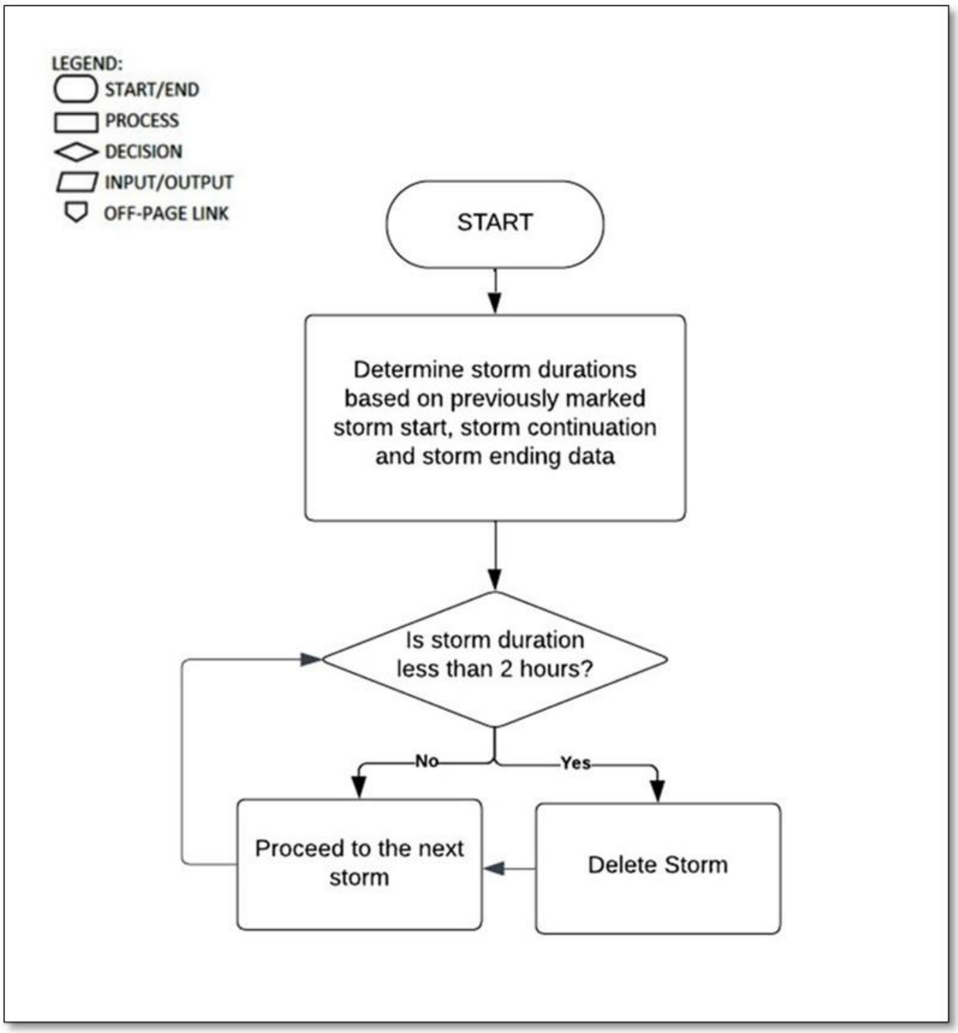

Figure 3-6 Algorithm for Deleting 1-hour Storms

3.4.2 Algorithm for Time-based Parametric Wave Prediction

If selected time window concept is Continuous Data the computational tool only checks if there are previous wind speed data for a duration of the input time window value. So, if time window is input to the computational tool as 10 hours, the computational tool checks all the rows and checks if there are ten consecutive previous wind data including the row being checked. If so, computational tool gets the storm duration as ten hours, average wind speed as arithmetic mean of the ten consecutive previous wind data including the one being worked on and fetch length as the average corresponding fetch length of weighted average of wind directions, averaged according to the square of wind speeds for ten consecutive previous wind data including the one being worked on. Then computational tool runs the code for the parametric wave prediction methods at every hour where there is storm duration, average wind speed and fetch length values.

For the other two time window concepts, the computational tool works according to the storm conditions. In both concepts the computational tool first determines the storms, marks all data as as “no storm”, “storm start”, “storm continuation” or “storm ending” data and also determines the duration of storms. The computational tool then starts to check all data in ascending order of date and time. When it comes to a storm data it first determines the duration of storm at that point. At “storm start” data storm duration is taken as 1 hour and increases 1 hour in the next step until the determined time window value. If time window concept is “User-Defined”, then the maximum storm duration will be the time window value input at the user interface. Otherwise, if it is “Storm Duration” the computational tool will take the time window value at every “storm start” data as the total storm duration of that storm.

When the storm ends, the computational tool will continue to give storm duration values equal to the time window value to the data after storm finish up to one hour less than time window value. So that, one storm value will be left in the selected storm duration.

So, the computational tool first determines the storm duration values for every data for which the calculations will be made with parametric wave prediction methods. And after we have the data for every calculation hour, the computational tool starts to calculate corresponding average wave height and fetch length for every calculation hour according to the storm values. So, if storm duration is n, the average wind speed and fetch length are calculated for previous n hour of data including the current hour. Average wind speed is the simple arithmetic mean of wind speed values and fetch length is the corresponding fetch length of weighted average of wind directions as described in Chapter 2.1.2.

All parametric wave prediction methods used in this study in the form of basic functions of storm duration (t), fetch length (F) and average wind speed (U_A) as in equations Eq.34 and Eq.35 below.

$$H_s = f(t, F, U_A) \quad Eq.34$$

$$T_p = f(t, F, U_A) \quad Eq.35$$

So when three variables are known the computational tool is ready to calculate significant wave height (H_s) and corresponding peak period (T_p) and the computational tool starts to calculate H_s and T_p for every hour starting from the first date and time in the data list in the ascending order of date and time. The flowchart for algorithm for time-based wave prediction methods are given in the figures Figure 3-7, Figure 3-8 and Figure 3-9 below.

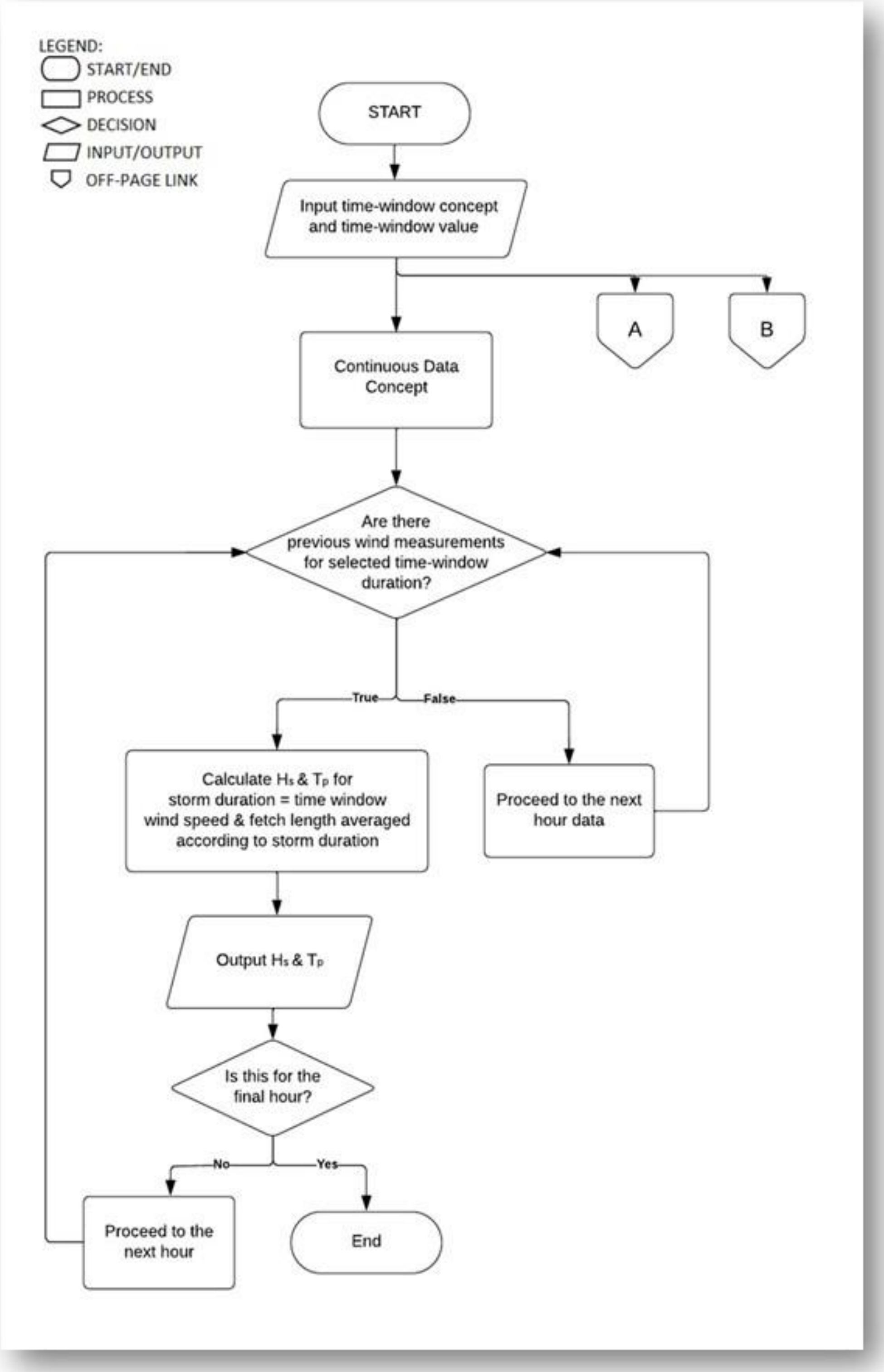

Figure 3-7 Algorithm for Time-Based Analysis 1/3

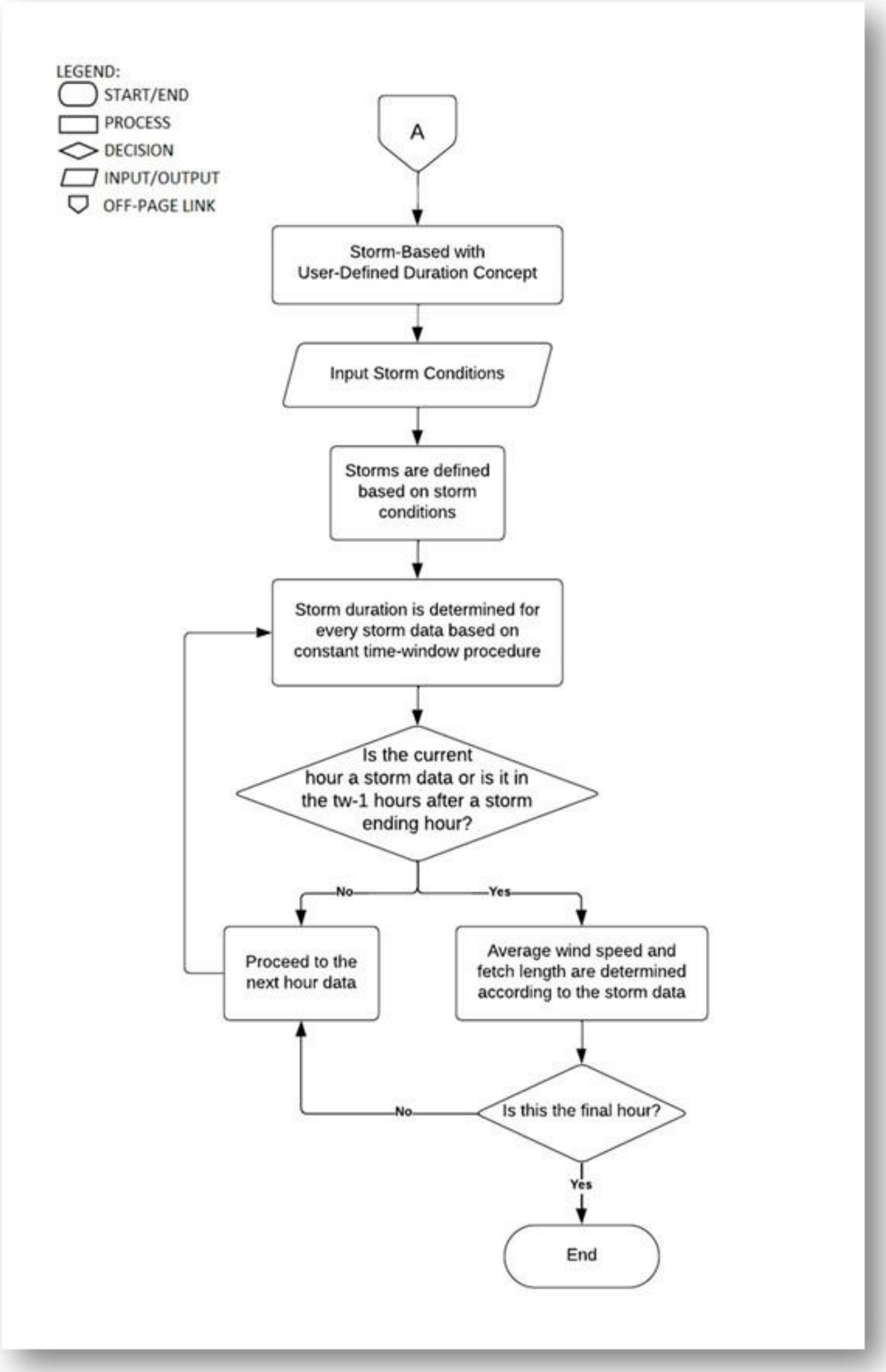

Figure 3-8 Algorithm for Time-Based Analysis 2/3

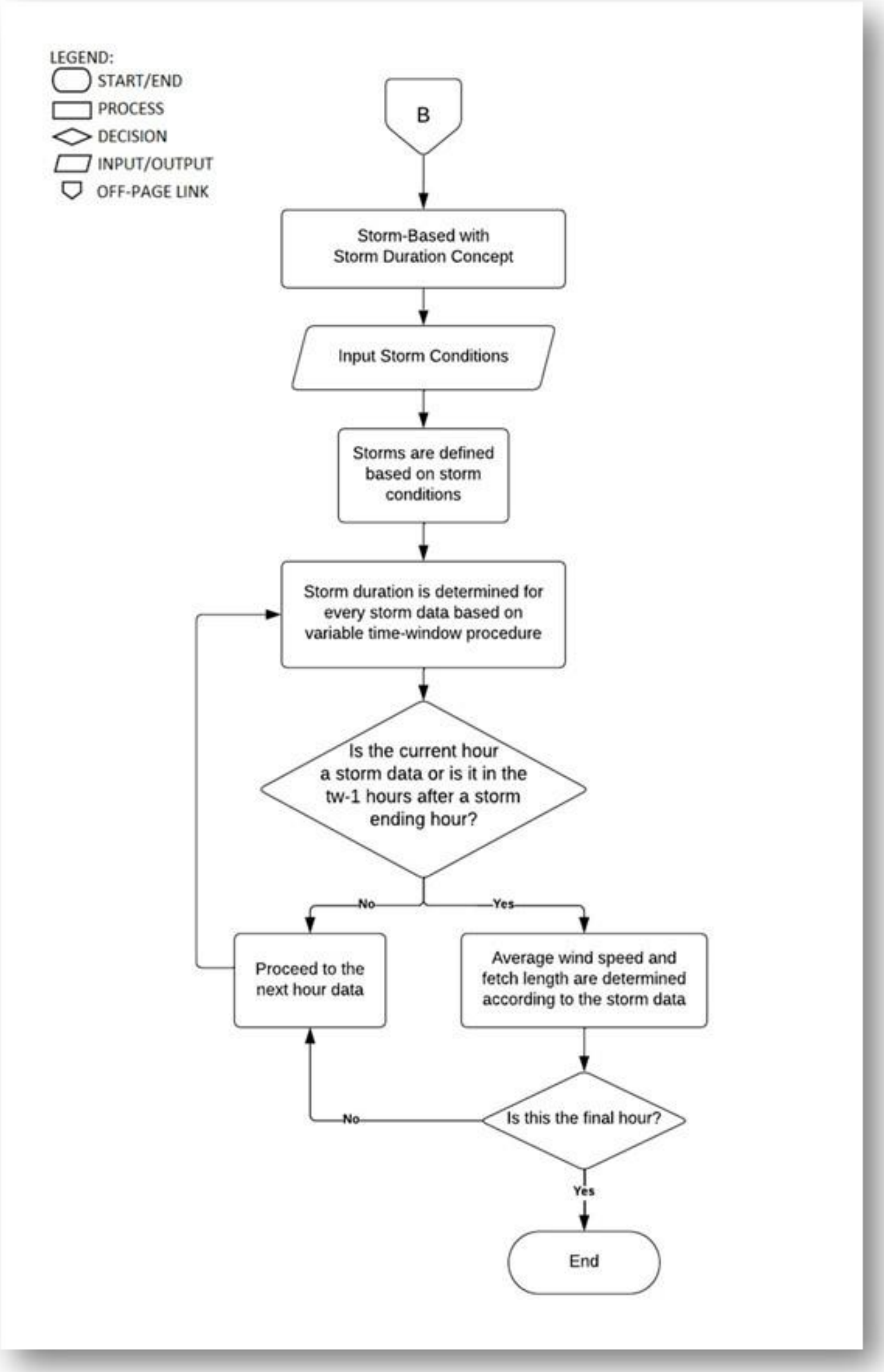

Figure 3-9 Algorithm for Time-Based Analysis 3/3

3.5 Outputs of the Computational Tool

After the computational tool is run and all calculations with the parametric wave prediction methods are done the computational tool creates data tables and graphs as output. The results of the parametric wave prediction method calculations are the desired output. However, to be able to review the results easily and give outputs related to measured-calculated wave height comparisons computational tool continues processing and creates easily reviewable tables and graphs. The outputs of the computational tool may be categorized in two groups, storm properties and measured-calculated wave comparisons.

3.5.1 Storm Properties

First table created is for the storm properties. At this point all data has been marked as “no storm”, “storm start”, “storm continuation” and “storm ending” and all storms were named with a unique name. So, basically all the storms have already been determined at this point. The computational tool starts to work on every storm to calculate values which may give an information about the properties of the storm climate of the location. This information then may be related to selected storm conditions input when computational tool was first started. The storm properties determined are as below.

- Duration: the total duration of the storm.

- Average direction: Average wind direction of the azimuth direction values in the storm.

- Maximum direction: the maximum value of azimuth direction values in the storm.

- Minimum direction: the minimum value of azimuth direction values in the storm.

- Average wind speed is the arithmetic mean of the wind speed values in the storm.

- Maximum wind speed: the maximum value of wind speed in the storm.

- Minimum wind speed: the minimum value of wind speed in the storm.

An example storm properties table created by the computational tool is shown in Table 3-4 below.

Table 3-4 Storm Properties Table

	A	B	C	D	E	F	G	H	I	J	K	L
1	Storm name	Duration	Average Direction	Max Direction	Min Direction	Hourly Max Direction Change	Max Direction Change Acc. to Average	Average Wind Speed	Max Wind Speed	Min Wind Speed	Hourly Max. Wind Speed Change	Max Wind Speed Change Acc. to Average
2	Storm - 1	3	275	291	260	31	16	3.3	4	3	1	0.7
3	Storm - 2	5	219	251	171	33	48	4.3	5.3	3.5	1.8	1
4	Storm - 3	6	203	237	123	107	80	5.9	7.3	3.6	1.8	2.3
5	Storm - 4	29	144	203	117	44	59	7.2	10.3	3.3	2.2	3.9
6	Storm - 5	17	303	343	274	24	40	8.8	13.8	3.5	1.5	5.3
7	Storm - 6	2	199	202	197	5	3	4	4.6	3.5	1.1	0.6
8	Storm - 7	20	162	290	116	88	128	4.9	7.7	3.1	2.7	2.8
9	Storm - 8	5	329	340	298	34	31	4.6	5.7	3.1	2.3	1.5
10	Storm - 9	11	216	250	195	15	34	7.5	9.6	3.9	2.3	3.6
11	Storm - 10	5	281	338	243	53	57	4.9	5.8	3.5	2.3	1.4
12	Storm - 11	55	256	354	51	117	155	5.5	7.7	3.2	2	2.3
13	Storm - 12	7	167	192	143	33	25	4.1	4.7	3.4	1.2	0.7
14	Storm - 13	10	300	338	269	26	38	4	4.8	3.3	0.7	0.8
15	Storm - 14	15	185	218	149	40	36	7.4	10.1	4.4	2	3
16	Storm - 15	4	330	360	297	35	33	6.1	7.8	3.9	2.6	2.2

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Using this table some information regarding the storm climate of the location may be obtained. These information regarding the storm climate may be average duration of storm, average maximum wind speed of storms, average wind directions of the storms and also average of maximum wind speed and direction changes of the storms. All these information may give an idea about storm conditions to be selected at the start of the computational tool. For example, if average wind speed of storms at a location is 4 m/s at a location then a minimum wind speed storm condition of 5m/s may not be a good idea. It should be mentioned here that, these storm properties are determined according to the storm conditions input to the computational tool by the user and selecting new storm conditions after seeing this table will result in another table. So, this selection of better storm conditions process is an iterative process. Some example histograms from the storm properties are shown in the figures Figure 3-10, Figure 3-11 and Figure 3-12 below.

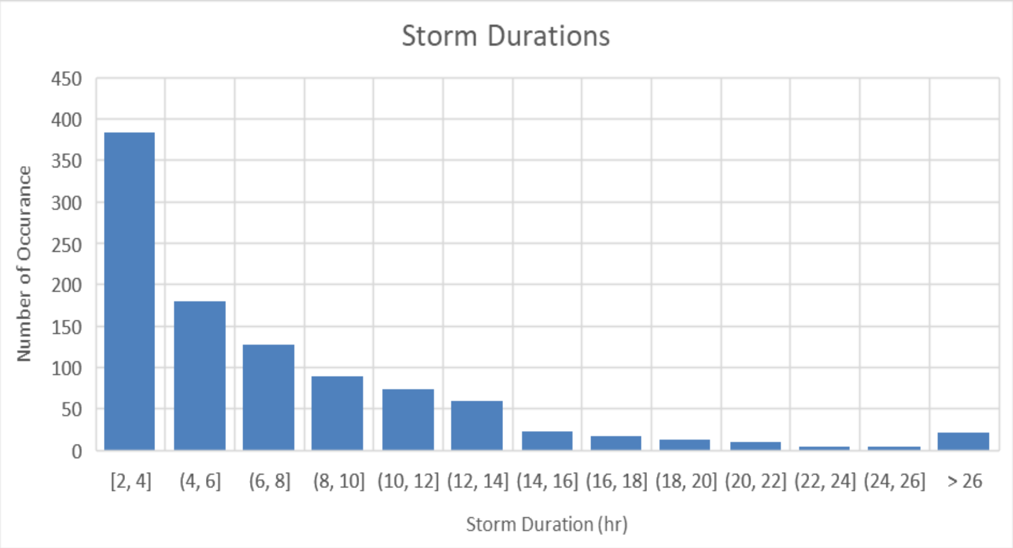

Figure 3-10 Storm Durations, Antalya (U_{min}=3m/s , ΔU =3m/s, ΔΘ 120°)

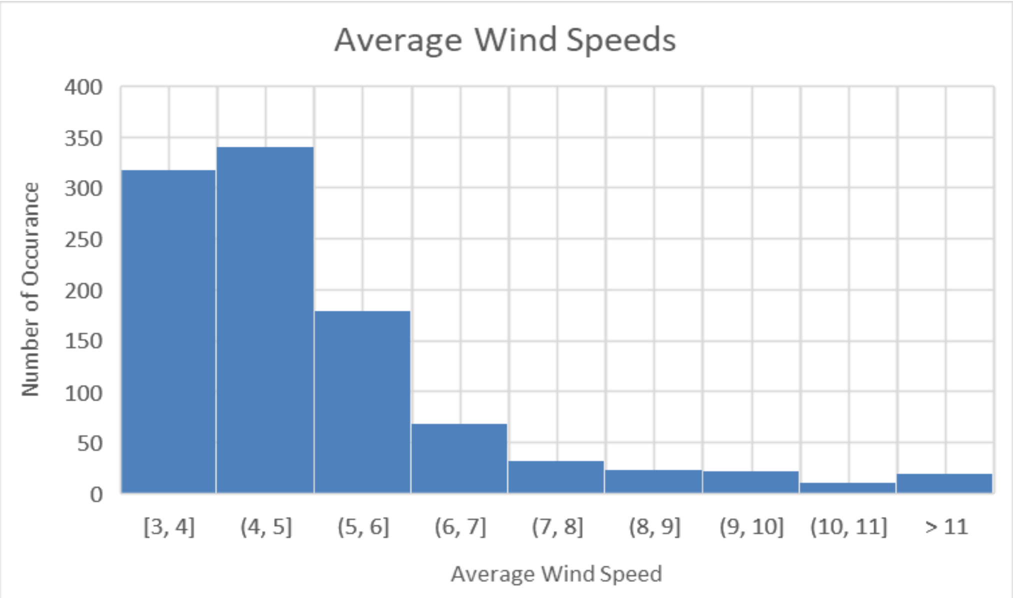

Figure 3-11 Storm Average Wind Speeds, Antalya (U_{min}=3m/s , ΔU =3m/s, ΔΘ 120°)

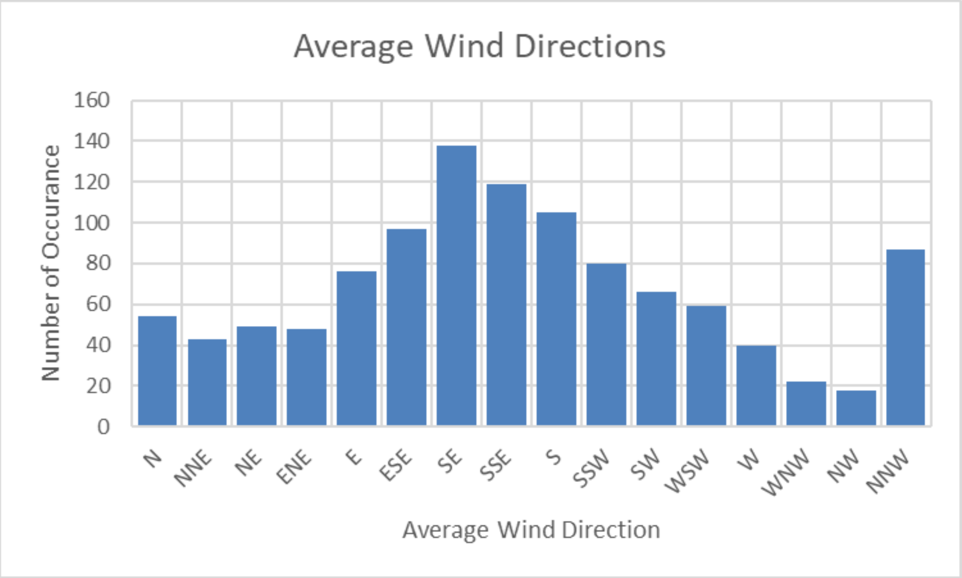

Figure 3-12 Storm Average Wind Directions, Antalya (U_{min}=3m/s , ΔU =3m/s, ΔΘ 120°)

3.5.2 Error Statistics

Other than storm properties, the computational tool also creates a table and graphs for comparison of measured and calculated waves. All the measured and calculated wave height and period values are taken in this table and error and accuracy calculations are made on this table. Error and accuracy calculations are made for data for which both measured and calculated wave heights are greater than 0.5m. Other data is not taken into consideration for error and accuracy calculations and also not considered in the graphs. Table 3-5 below shows an example table for error and accuracy calculations. Measured and calculated wave height and periods are taken in this table. The four columns on the right side of his table are calculations between observed and predicted value for error calculations. As seen on the Table 3-5, when measured or calculated significant wave height is not greater than 0.5m the observed and predicted value calculations are not made.

Table 3-5 Error and Accuracy Calculation Table

	A	B	C	D	E	F	G	H	I	J	K	L
1	Year	Month	Day	Hour	Measured Hs	Measured Tp	CEM Hs	CEM Tp	O-P	O	(O-P)^2	O^2
402	2015	4	10	4	0.88	6.5	0.55	2.69	0.33	0.88	0.1089	0.7744
403	2015	4	10	5	0.79	5.5	0.55	2.69	0.24	0.79	0.0576	0.6241
404	2015	4	10	6	0.71	5.3	0.55	2.69	0.16	0.71	0.0256	0.5041
405	2015	4	10	7	0.67	5.7	0.5	2.58				
406	2015	4	10	8	0.56	6	0.45	2.47				
407	2015	4	10	9	0.49	6.4	0.17	1.17				
408	2015	4	10	10	0.55	4.8	0.34	1.78				
409	2015	4	10	11	0.56	5.3	0.5	2.25				
410	2015	4	10	12	0.56	5	0.65	2.64	-0.09	0.56	0.0081	0.3136
411	2015	4	10	13	0.62	4.7	0.83	3.05	-0.21	0.62	0.0441	0.3844
412	2015	4	10	14	0.77	4.6	0.98	3.38	-0.21	0.77	0.0441	0.5929
413	2015	4	10	15	0.85	4.7	1.05	3.49	-0.2	0.85	0.04	0.7225
414	2015	4	10	16	0.88	4.3	1.07	3.51	-0.19	0.88	0.0361	0.7744
415	2015	4	10	17	0.78	4.3	1.04	3.47	-0.26	0.78	0.0676	0.6084
416	2015	4	10	18	0.82	4.5	1.03	3.45	-0.21	0.82	0.0441	0.6724
417	2015	4	10	19	0.81	4.6	0.99	3.4	-0.18	0.81	0.0324	0.6561
418	2015	4	10	20	0.86	4.7	0.96	3.36	-0.1	0.86	0.01	0.7396

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Some error estimation methods were considered, and normalized root mean squared error (NRMSE) and NBIAS were considered to be the best methods for this study.

3.5.2.1 NRMSE

NRMSE is a method to see the error in predicted data by comparing it to the observed data. The lower the calculated NRMSE the closer the predicted values to the observed values. NRMSE is the division of root mean squared error (RMSE) to the average of observed data. The formula for RMSE is as given in Eq.36 below.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \qquad Eq.36$$

Where, N is the total number of samples, P_i is the predicted value and O_i is the observed value. NRMSE is simply the division of RMSE to the arithmetic mean of the observed data as in Eq.37.

$$NRMSE = \frac{RMSE}{\bar{O}} \qquad Eq. 37$$

Where $\bar{O}$ is the mean of observations.

3.5.2.2 NBIAS

BIAS and NBIAS are used to see underestimation and overestimation of the predicted values when compared to observed values. A negative BIAS and NBIAS means the predicted values are higher than observed values and positive BIAS and NBIAS means predicted values are less than the observed data. NBIAS is the normalized BIAS and it is basically the division of BIAS to the sum of all observed data. The formula for NBIAS is as given below in Eq.38.

$$NBIAS = \frac{\sum_{i=1}^{N} Oi - Pi}{\sum_{i=1}^{N} Oi} \qquad Eq. 38$$

3.6 Wind and Wave Data: Antalya & Mersin

3.6.1 Geographical location of buoys

The wind and wave data obtained from the buoy readings in Antalya and Taşucu, Mersin were located in eastern Mediterranean, at coordinates 36°43’00’’N 31°11’00’E and 36°04’50’’N 33°46’50’’E, respectively. Both buoys are almost 11km off the shore from the mainland. According to Google Earth data, depth in Antalya buoy location is are around 430m and depth in Mersin buoy location is around 150m. So, waves may be considered in deep water. A Google Earth image of eastern Mediterranean showing both locations is given below in Figure 3-13. As seen on the image both buoys have a land boundary to the north. Antalya buoy has long fetches from S, SW and SSE directions, whereas Mersin buoy has long fetches only from SW only.

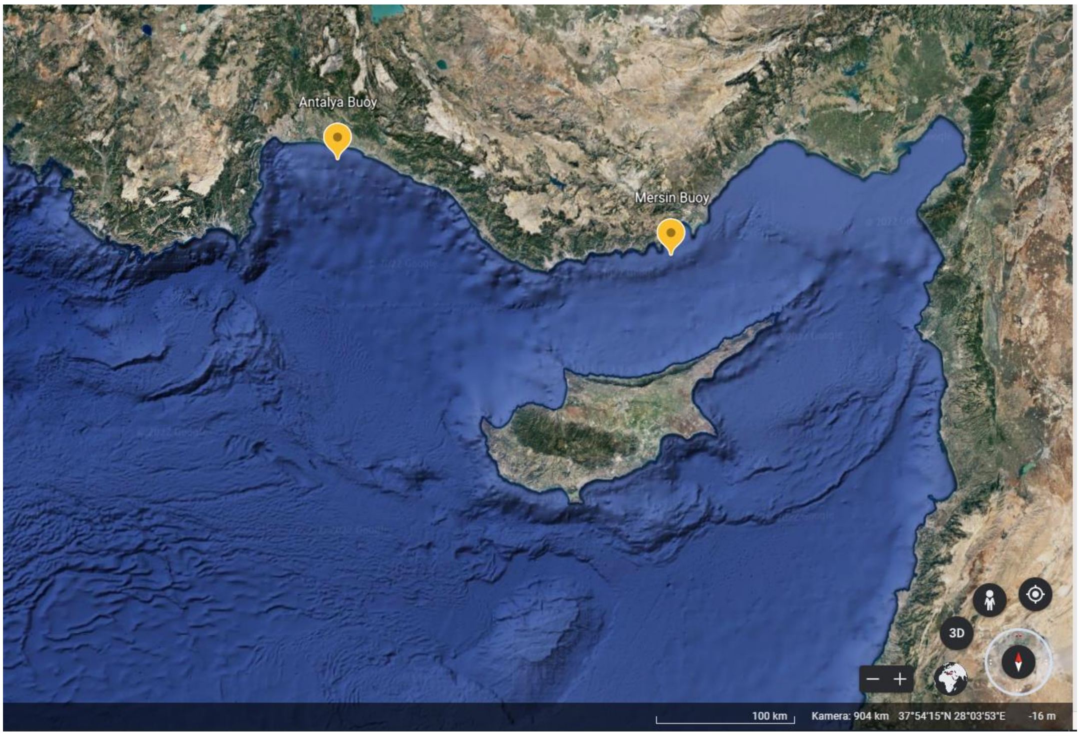

Figure 3-13 Google Earth Image Showing the Exact Buoy Locations

3.6.2 Wind Data Readings of the Buoys

The wind data readings from Antalya and Taşucu, Mersin are from years 2015 and 2016. The exact intervals are March 24, 2015 – October 31, 2016 for Antalya buoy and March 31, 2015 – September 27, 2016 for Taşucu, Mersin buoy. Wind data readings have a resolution of 1 hour in both data sets. Both data have date, hour, average wind direction, average wind speed, maximum wind direction, maximum wind speed and the minute information for the maximum wind speed in a 10 minute resolution. Antalya buoy has made readings for 91.6% of the total time period i.e. 12,905 hourly readings in a time period of 14,095 hours. Mersin buoy has made readings for 96.6% of the total time period i.e. 12,662 hourly readings in a time period of 13,107 hours.

Wind roses created from the buoy readings for Antalya and Taşucu, Mersin for the given time periods are shown below in Figure 3-14 and Figure 3-15, respectively. It is seen on the wind roses that majority of wind speed readings in Antalya were between 0-4m/s range whereas in Mersin majority of wind speed readings are between 4-8m/s. The prevailing wind directions in Antalya and Mersin are SE and WSW, respectively and the direction of winds in Mersin were more concentrated on a smaller angular direction interval.

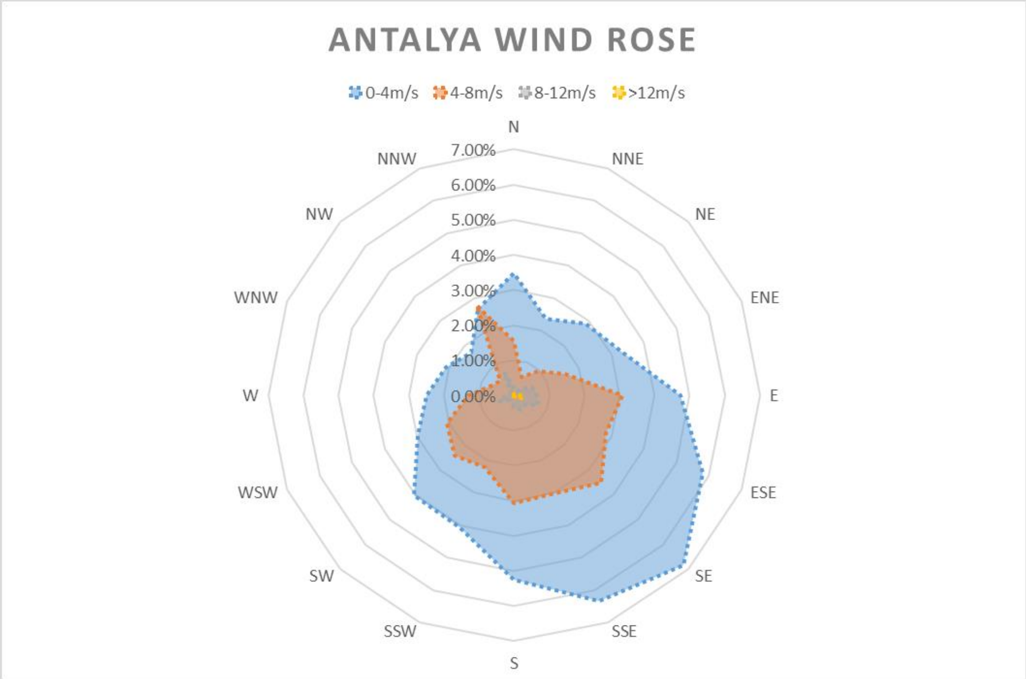

Figure 3-14 Antalya Wind Rose

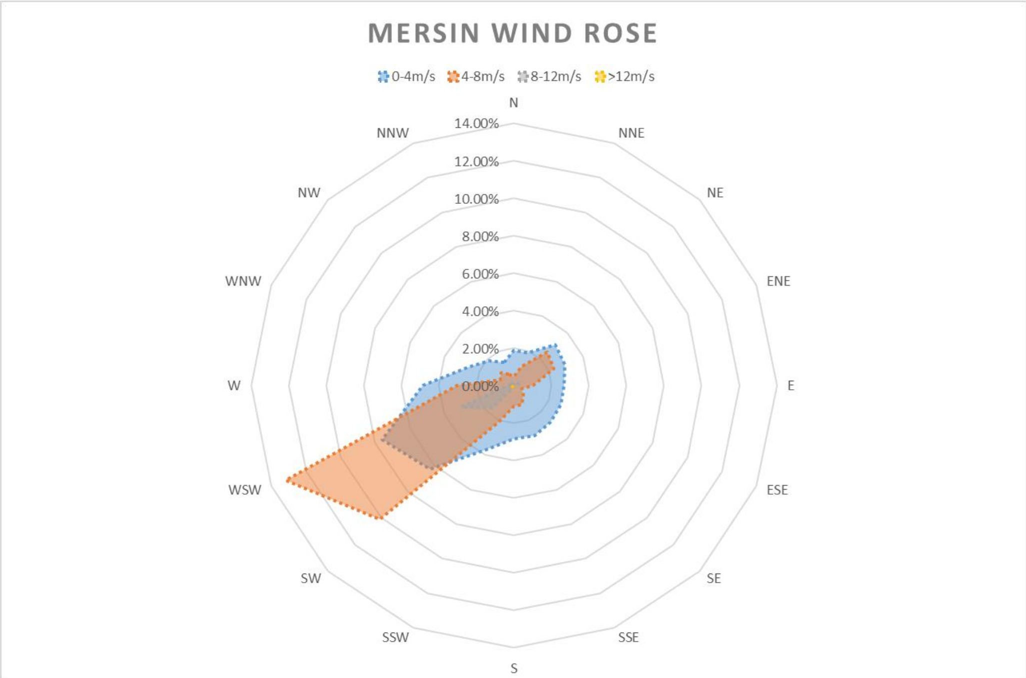

Figure 3-15 Mersin Wind Rose

3.6.3 Wave Data Readings of the Buoys

Wave data readings of Antalya and Mersin buoys are also from years 2015 and 2016. Exact dates for the readings for Antalya and Mersin buoys are March 24, 2015-October 27, 2016 and April 1, 2015-October 27,2016, respectively. Wave readings of the buoys have a resolution of 30 minutes. The data from the buoys includes date, hour, minute, significant wave height, maximum wave height, wave direction, average wave period, peak wave period and wave length. The data also includes current speed and direction information with a 30 minute resolution. Antalya has made readings 91.0% of the whole period and Mersin buoy has made readings 97.2% of the whole period. The exact data count is 25,450 readings in 27,974 half hours for Antayla and 25,468 readings in 26,214 half hours for Mersin. The wave data used in the developed computational tool was used for comparison with calculated wave data (based on wind data). Since, wind data has a 1 hour resolution only half of the wave data were used in this study which was selected as the maximum of two significant wave height readings for every hour.

The wind roses created from the data of the buoys are shown below in Figure 3-16 and Figure 3-17. As seen on the wave roses the majority of the significant wave height of waves in Antalya are in the 0-0.5m range, whereas in Mersin majority of the significant wave height are in the 0.5m and 1.5m range. Since the wind roses show higher wind speeds in Mersin than Antalya, it is a reasonable outcome that wave heights in Mersin are also higher than wave heights in Antalya.

The direction of the waves in Antalya are from S and SSW direction and in Mersin direction of almost all the waves are WSW. The wave directions are in the directions of longest fetches for both buoys.

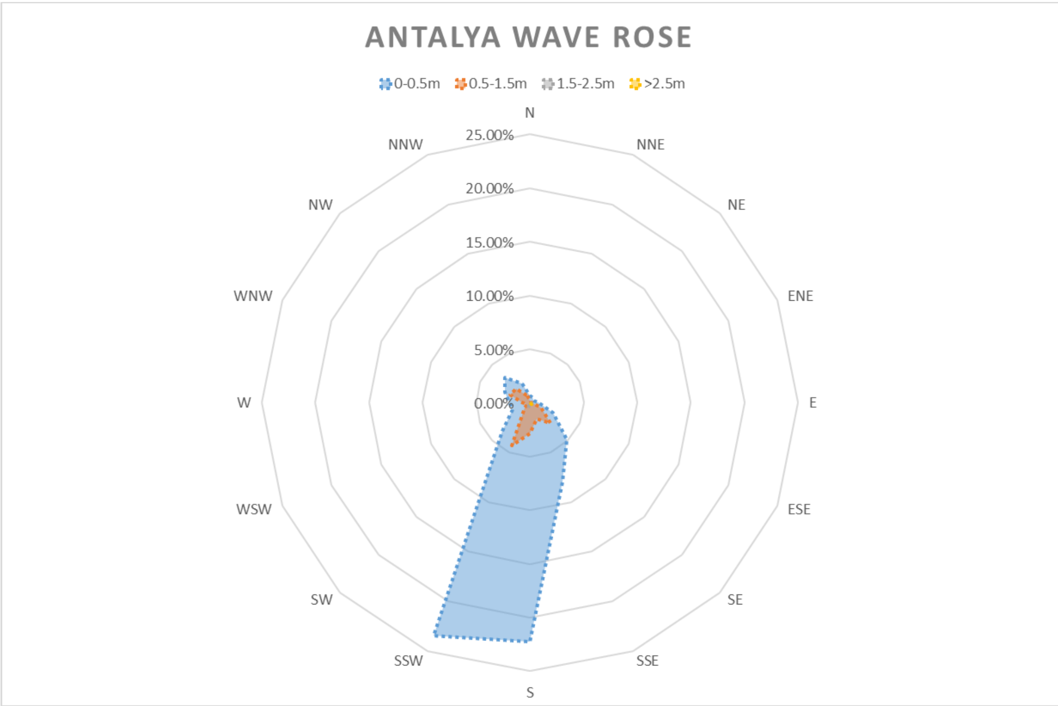

Figure 3-16 Antalya Wave Rose

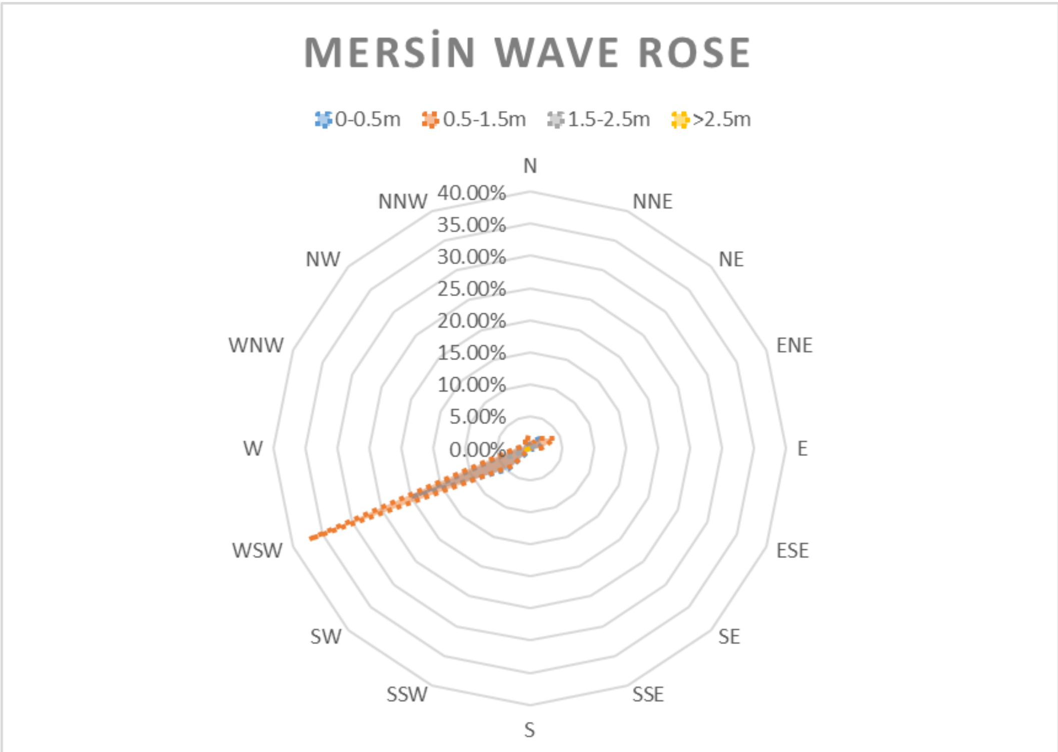

Figure 3-17 Mersin Wave Rose

CHAPTER 4

RESULTS AND DICUSSIONS

4.1 Wave Hindcasting and Results

In this study developed computational tool was used to analyze the effectiveness of parametric wave prediction methods in time-based calculations. Effectiveness of the proposed storm duration concepts to use these parametric methods in a time-based manner was also analyzed. For this purpose, existing wind and wave measurements data from two buoys in Turkey were used. One of the buoys was located near Antalya with buoy coordinates 36°43’00’’N 31°11’00’E and the other one was located near Taşucu, Mersin with buoy coordinates 36°04’50’’N 33°46’50’’E. Both buoys made readings for almost 18 months between 2015 and 2016. The buoys made wind speed measurements at an elevation of approximately 4m above the sea level. The fetch lengths of the buoy locations were calculated as shown on figures in Chapter 2.1.2, i.e. Figure 2-1 and Figure 2-2. After inputting all data in the computational tool and starting to make runs it was seen that different time window concepts, different time window values and conditions resulted in different errors in terms of NRMSE and NBIAS values and many trials were made for different values of these variables.

For these analysis, the Coastal Engineering Manual method described in Chapter 2.2.2 was used.

4.1.1 Results for Continuous Data Concept

The time window values were taken between 6 hours and 16 hours for both Antalya and Mersin. The computational tool was run with 2 hour intervals between 6 and 16 hours for time window values. In Antalya the minimum NRMSE was seen between 6 hours and 8 hours and two more runs were made close to these values. So, time window values for which the computational tool was run with Antalya data are 6, 7, 8, 9, 10, 12, 14 and 16 hours. The calculated NRMSE and NBIAS values are given in Table 4-1 below. As seen on the Table 4-1 minimum NRMSE was at 7 hours time window and minimum NBIAS was at 12 hours time window.

Table 4-1 Antalya Continuous Data Concept NRMSE results

	TW=6	TW=7	TW=8	TW=9	TW=10	TW=12	TW=14	TW=16
NRMSE	0.241	**0.233**	0.236	0.239	0.240	0.251	0.285	0.308
NBIAS	0.189	0.143	0.103	0.077	0.053	**-0.011**	-0.085	-0.140

Same calculations were performed in Mersin. Minimum NRMSE was at 14 hours. So, computational tool was also run for 13 hours and 15 hours time windows. The minimum NRMSE in Mersin was at 14 hours time window and minimum NBIAS was at 16 hours as seen on the Table 4-2 below.

Table 4-2 Mersin Continuous Data Concept NRMSE results

	TW=6	TW=8	TW=10	TW=12	TW=13	TW=14	TW=15	TW=16
NRMSE	0.248	0.196	0.164	0.149	0.144	**0.143**	0.146	0.150
NBIAS	0.413	0.325	0.248	0.183	0.148	0.114	0.083	**0.056**

The data was almost for 18 months for both Antalya and Mersin and NRMSE and NBIAS value were calculated for all the data of this 18 months. The graphs for Antalya and Mersin were prepared for the time window values where the NRMSE and NBIAS were minimum and two graphs for both Antalya and Mersin are shown in Figure 4-1, Figure 4-2, Figure 4-3 and Figure 4-4. These graphs are examples from the storms which showed a close relation between measured and calculated wave heights. The dates were selected randomly. It should be noted that, there are also a number of storms which do not show similar tendency.

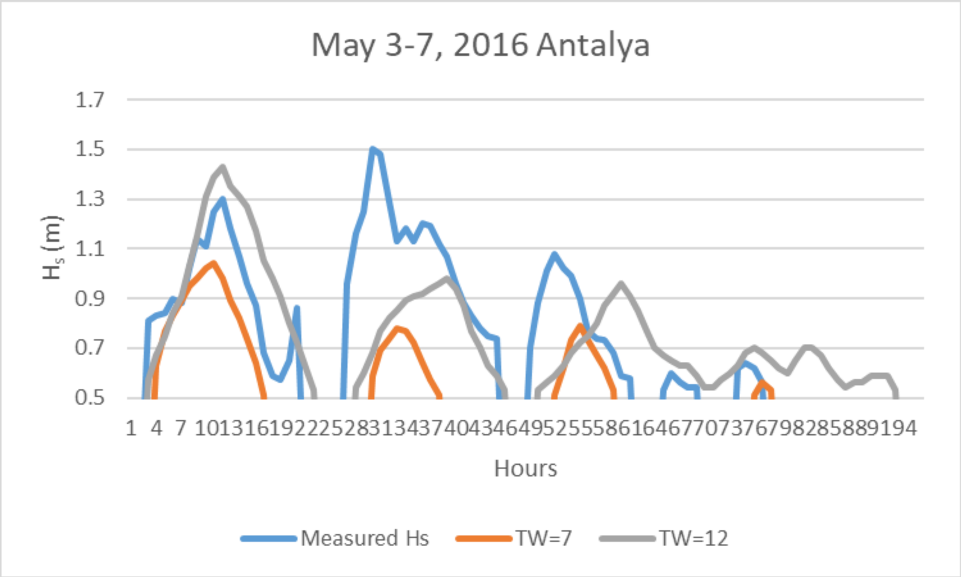

Figure 4-1 Antalya - Measured-Calculated Data Comparison for Continuous Data Concept -1 (TW=7 if for min. NRMSE and TW=12 is for min. NBIAS)

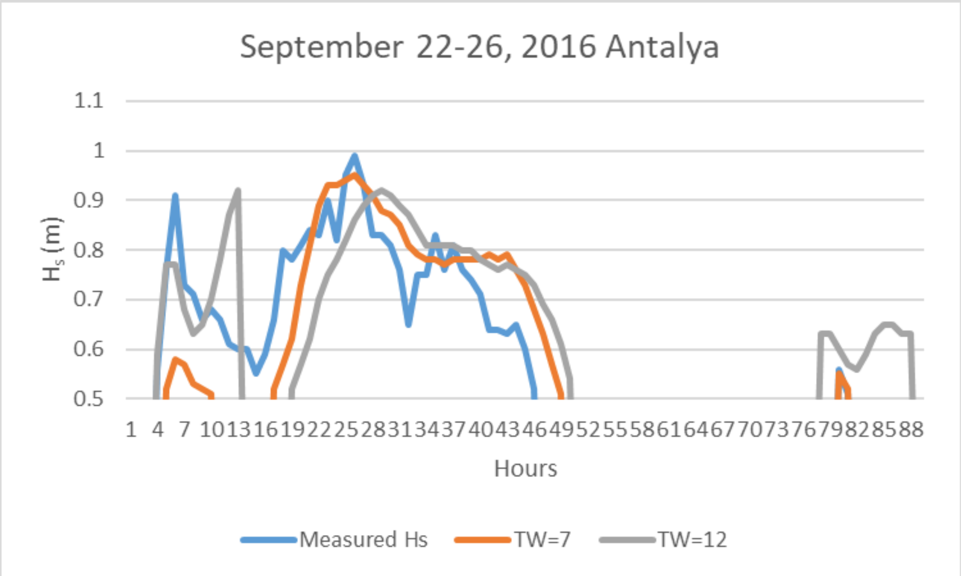

Figure 4-2 Antalya - Measured-Calculated Data Comparison for Continuous Data Concept -2 (TW=7 if for min. NRMSE and TW=12 is for min. NBIAS)

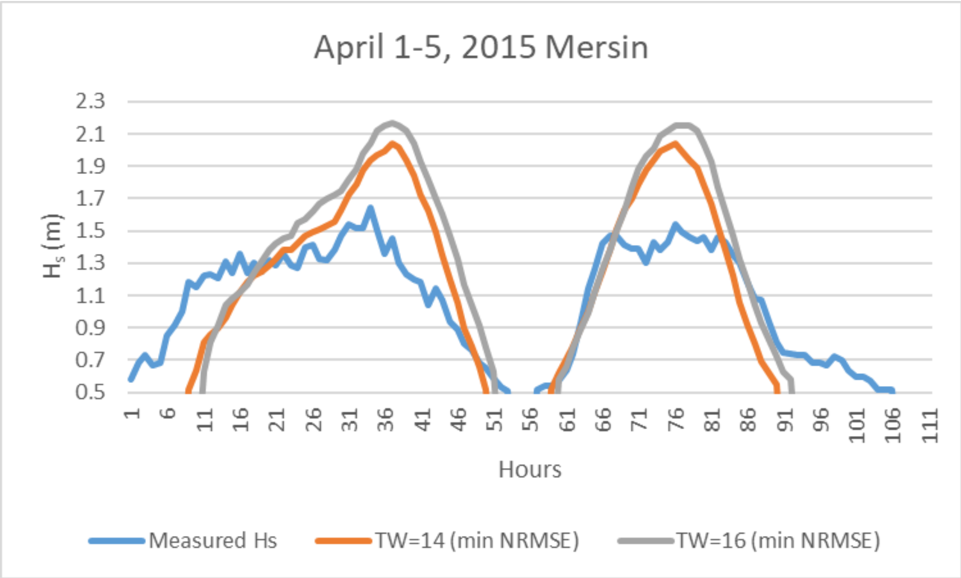

Figure 4-3 Mersin - Measured-Calculated Data Comparison for Continuous Data Concept -1

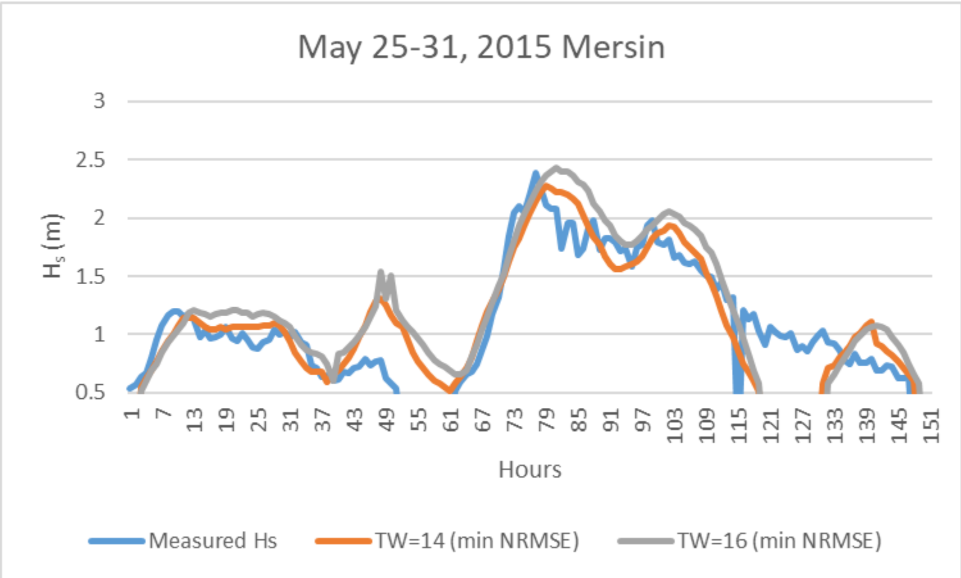

Figure 4-4 Mersin - Measured-Calculated Data Comparison for Continuous Data Concept -2

From these graphs, it is seen that the time window concept without storm conditions has the capacity to predict significant wave height of some storms at a satisfactory level. However, this is not valid for all the storms.

4.1.2 Results for Storm-Based with User-Defined Duration Concept

For storm-based calculations the definition of storms will be used and there are storm condition variables other than the time window value. The computational tool was run for different values of minimum wind speed (U_{min}), maximum wind speed change (ΔU) and maximum wind direction change ($\Delta\Theta$) along with the time window value (TW).

4.1.2.1 Computational Tool Run for Antalya Data

For Antalya first runs were made with following storm conditions U_{min}=4m/s, ΔU=3 /s, $\Delta\Theta$=30° for different time window values between 2 hours and 16 hours. The minimum NRMSE and minimum NBIAS were at 6 hours and 10 hours time window values, respectively. The results may be seen in Table 4-3.

Table 4-3 Antalya Time Window NRMSE Calculations for Storm-Based with User-Defined Duration Concept

	NRMSE	NBIAS
TW=2	0.405	0.522
TW=4	0.266	0.283
TW=6	**0.239**	0.154
TW=8	0.266	0.073
TW=10	0.295	0.029
TW=12	0.331	**-0.015**
TW=14	0.374	-0.050
TW=16	0.395	-0.069

Then the computational tool was run for different minimum wind speed condition for storms. Time window value was taken as 6 hours, since minimum NRMSE was at 6 hours. Maximum wind speed and direction changes were taken as

ΔU=3m/s, $\Delta\Theta$=30°, respectively. The minimum conditions tried were between 2m/s and 5m/s with 0.5m/s intervals. After these runs the minimum NRMSE and minimum NBIAS were both at U_{min}=3 m/s. The results of computational tool runs for different values of U_{min} are shown in Table 4-4 below.

Table 4-4 Antalya U_{min} NRMSE Calculations for Storm-Based with User-Defined Duration Concept

	NRMSE	NBIAS
U_{min}=2	0.222	0.143
U_{min}=2.5	0.222	0.143
U_{min}=3	**0.222**	**0.143**
U_{min}=3.5	0.232	0.150
U_{min}=4	0.239	0.154
U_{min}=4.5	0.239	0.156
U_{min}=5	0.238	0.155

Then the same procedure was applied for the maximum wind speed change condition. The values tried were between 1m/s and 4m/s with 0.5m/s intervals. Another trial was made with no wind speed change condition for storms as some studies resulted in better results without maximum wind speed change conditions (Sahin et al., 2007). Time window value was again 6 hours and other storm conditions were U_{min}=3m/s and $\Delta\Theta$=30°. The minimum NRMSE and minimum NBIAS were found at ΔU=3.5m/s. The results for these runs are shown at the Table 4-5 below.

Table 4-5 Antalya ΔU NRMSE Calculations for Storm-Based with User-Defined Duration Concept

	NRMSE	NBIAS
ΔU=1	0.275	0.273
ΔU=1.5	0.253	0.182
ΔU=2	0.237	0.144
ΔU=2.5	0.234	0.143
ΔU=3	0.222	0.143
ΔU=3.5	**0.216**	**0.134**
ΔU=4	0.233	0.147
ΔU=∞	0.246	0.164

Lastly, the maximum wind direction change condition was studied. This condition was studied for values between 15° and 135° with intervals of 15°. For wind direction change runs, time window value was taken as 6 hours, minimum wind speed and maximum wind speed change values were taken as 3m/s and 3.5m/s, respectively. Minimum NRMSE and minimum NBIAS were found at 120° and 60°, respectively. Results may be seen on Table 4-6 below.

Table 4-6 Antalya ΔΘ NRMSE Calculations for Storm-Based with User-Defined Duration Concept

	NRMSE	NBIAS
ΔΘ=15°	0.229	**0.128**
ΔΘ=30°	0.216	0.134
ΔΘ=45°	0.215	0.141
ΔΘ=60°	0.214	0.141
ΔΘ=75°	0.214	0.140
ΔΘ=90°	0.214	0.140
ΔΘ=105°	0.214	0.144
ΔΘ=120°	**0.214**	0.144
ΔΘ=135°	0.217	0.147

So, after the computational tool was run for all time window and storm condition variables. The variables giving the minimum NRMSE were;

Time window = 6 hours,

U_{min} = 3m/s,

ΔU =3.5m/s,

ΔΘ =120°,

The minimum NRMSE value obtained was 0.214 as seen on Table 4-6. The calculations show that each value changes the error results and iteratively NRMSE value may be minimized. It should be noted that time window value had the most significant effect on the NRMSE values. The NRMSE values calculated for different time window values resulted in NRMSE values between 0.239 and 0.405. Effect of storm conditions on NRMSE were not that significant and interpreting these NRMSE values may not lead to practical conclusions.

The Figure 4-5 and Figure 4-6 show the measured and calculated significant wave height comparisons for the dates which were used for Continuous Data concept for comparison purposes. The calculated curve in these graphs are for the value giving the minimum NRMSE, i.e. time window 6 hours, U_{min}=3m/s, ΔU =3.5m/s and ΔΘ =120°.

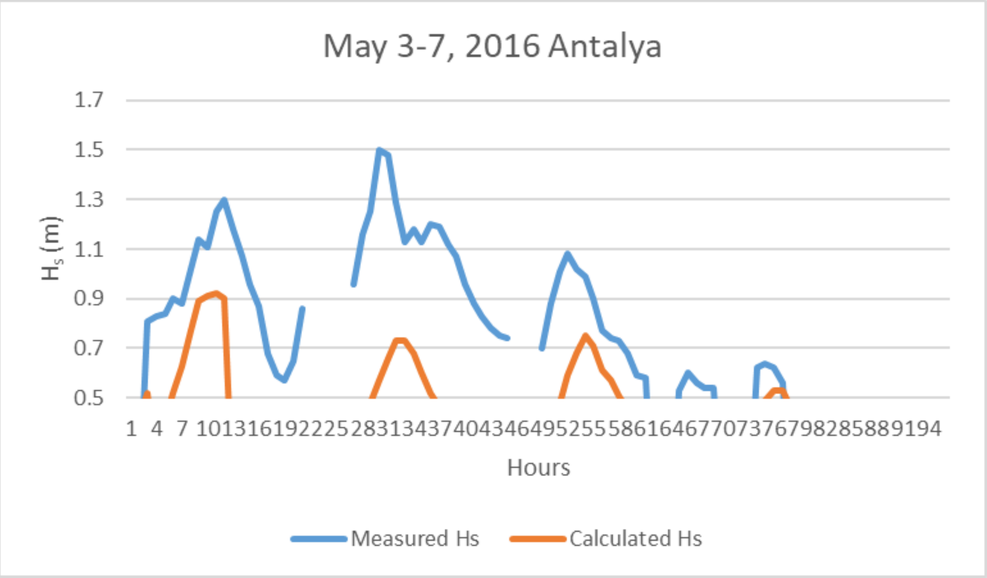

Figure 4-5 Antalya - Measured-Calculated Data Comparison for Storm-Based with User-Defined Duration Concept – 1

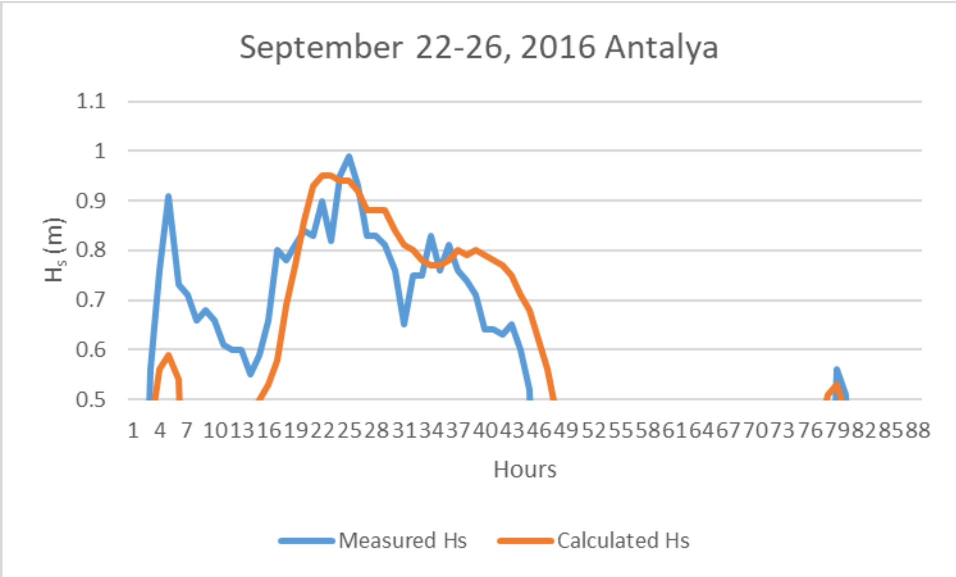

Figure 4-6 Antalya - Measured-Calculated Data Comparison for Storm-Based with User-Defined Duration Concept - 2

4.1.2.2 Computational Tool Run for Taşucu, Mersin Data

The same procedure applied to Antalya was also applied to the data from Taşucu, Mersin. So, first different time window values were tried with storm conditions U_{min}=4m/s , ΔU=3m/s , ΔΘ=30°. The minimum NRMSE and NBIAS values were found at 14 hour and 16 hours as shown on Table 4-7 below.

Table 4-7 Mersin Time Window NRMSE Calculations for Storm-Based with User-Defined Duration Concept

	NRMSE	NBIAS
TW=2	0.492	0.685
TW=4	0.338	0.525
TW=6	0.230	0.402
TW=8	0.171	0.308
TW=10	0.140	0.229
TW=12	0.127	0.163
TW=14	**0.127**	0.106
TW=16	0.137	**0.060**

Then taking the time window value 14 hours, computational tool was run for different values of minimum wind speed between 2m/s and 5m/s with intervals of 0.5m/s. Other two storm conditions were taken as ΔU=3m/s, ΔΘ=30°. The results of these runs are shown on Table 4-8 below. Minimum NRMSE and minimum NBIAS values were both at U_{min}=2.5m/s.

Table 4-8 Mersin Umin NRMSE Calculations for Constant Time Window, Storm-Based Calculations

	NRMSE	NBIAS
U_{min}=2	0.125	0.102
U_{min}=2.5	**0.125**	**0.102**
U_{min}=3	0.125	0.103
U_{min}=3.5	0.125	0.104
U_{min}=4	0.127	0.106
U_{min}=4.5	0.129	0.111
U_{min}=5	0.135	0.122

The computational tool was run for maximum wind speed change storm condition. This time time window value was taken as 14 hours, minimum wind speed condition was taken as 2.5m/s and maximum wind direction change condition was taken as 30°. As seen on Table 4-9 below, minimum NRMSE and minimum NBIAS values were at 2.5m/s and 4m/s, respectively.

Table 4-9 Mersin ΔU NRMSE Calculations for Storm-Based with User-Defined Duration Concept

	NRMSE	NBIAS
ΔU=1	0.180	0.239
ΔU=1.5	0.136	0.146
ΔU=2	0.121	0.115
ΔU=2.5	**0.117**	0.100
ΔU=3	0.125	0.102
ΔU=3.5	0.118	0.099
ΔU=4	0.118	**0.098**
ΔU=∞	0.120	0.100

The last storm condition the computational tool wan run for was maximum wind direction change. The computational tool was run for values between 15° and 135° with intervals of 15°. Time window value was 14 hours, minimum wind speed for storm condition was 2.5m/s and maximum wind speed change for storm condition was 2.5m/s. As seen on Table 4-10 below the minimum NRMSE and minimum NBIAS were at 45° and 60°, respectively.

Table 4-10 Mersin ΔΘ NRMSE Calculations for Storm-Based with User-Defined Duration Concept

	NRMSE	NBIAS
ΔΘ=15°	0.135	0.134
ΔΘ=30°	0.117	0.100
ΔΘ=45°	**0.115**	0.107
ΔΘ=60°	0.115	**0.105**
ΔΘ=75°	0.115	0.106
ΔΘ=90°	0.116	0.107
ΔΘ=105°	0.120	0.109
ΔΘ=120°	0.121	0.110
ΔΘ=135°	0.122	0.110

The minimum NRMSE value was obtained as 0.115. The variable to obtain the minimum NRMSE were;

Time Window = 14 hours,

U_{min} = 2.5m/s,

ΔU=2.5m/s,

ΔΘ=45°,

Table 4-7, Table 4-8, Table 4-9 and Table 4-10 show that selection of time window value had the most significant effect on NRMSE values.

Figure 4-7 and Figure 4-8 show the measured and calculated significant wave height comparisons for the same dates which were used for Storm-Based with User-Defined Duration concept for comparison purposes. The calculated curve in these graphs are for the value giving the minimum NRMSE, i.e. time window 14 hours, U_{min}=2.5m/s, ΔU =2.5m/s and ΔΘ =45°.

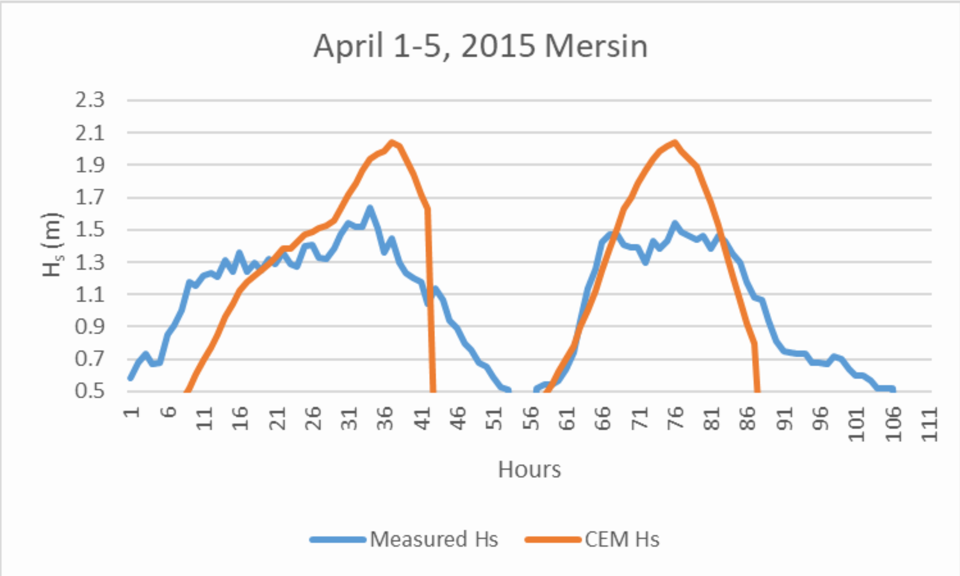

Figure 4-7 Mersin - Measured-Calculated Data Comparison for Storm-Based with User-Defined Duration Concept -1

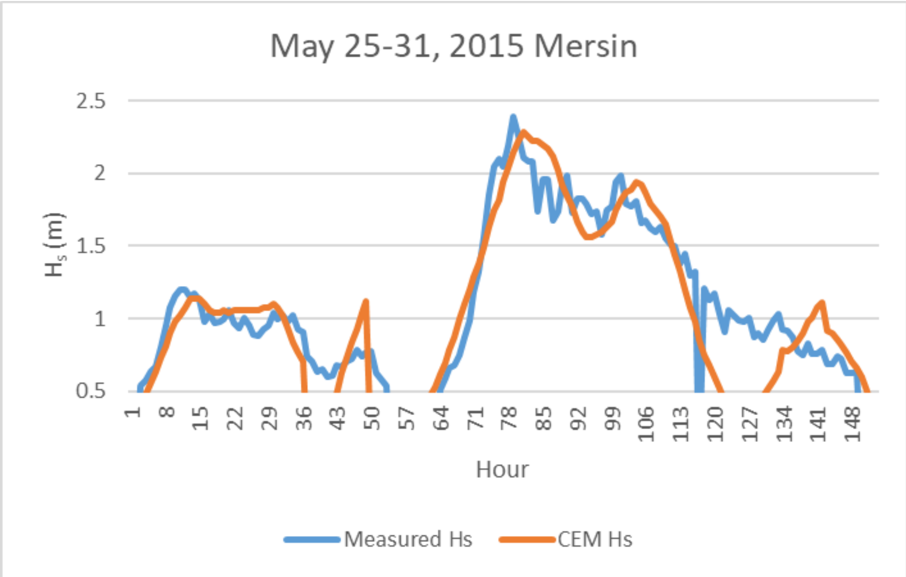

Figure 4-8 Mersin - Measured-Calculated Data Comparison for Storm-Based with User-Defined Duration Concept -2

4.1.3 Results for Storm-Based with Storm Duration Concept

Storm-Based with Storm Duration concept is the third and last method proposed to use parametric wave prediction methods in a time-based way. In this method only one run was made for both Antalya and Taşucu, Mersin measurements with the storm conditions giving the minimum NRMSE as show on Table 4-11 below. Time window value is not used in this concept.

Table 4-11 Storm-Based with Storm Duration Concept - Storm Conditions

	U_{min} (m/s)	ΔU (m/s)	ΔΘ (°)
Antalya	3	3.5	120
Taşucu, Mersin	2.5	2.5	45

The NRMSE and NBIAS values for Antalya and Taşucu, Mersin were as in Table 4-12 below.

Table 4-12 NRMSE and NBIAS values for Storm-Based with Storm Duration Concept

	NRMSE	NBIAS
Antalya	0.384	-0.128
Taşucu, Mersin	0.249	-0.054

The graphs were prepared for variable time window, storm-based concept as shown in Figure 4-9, Figure 4-10, Figure 4-11 and Figure 4-12 below for the same dates as the previous two concepts.

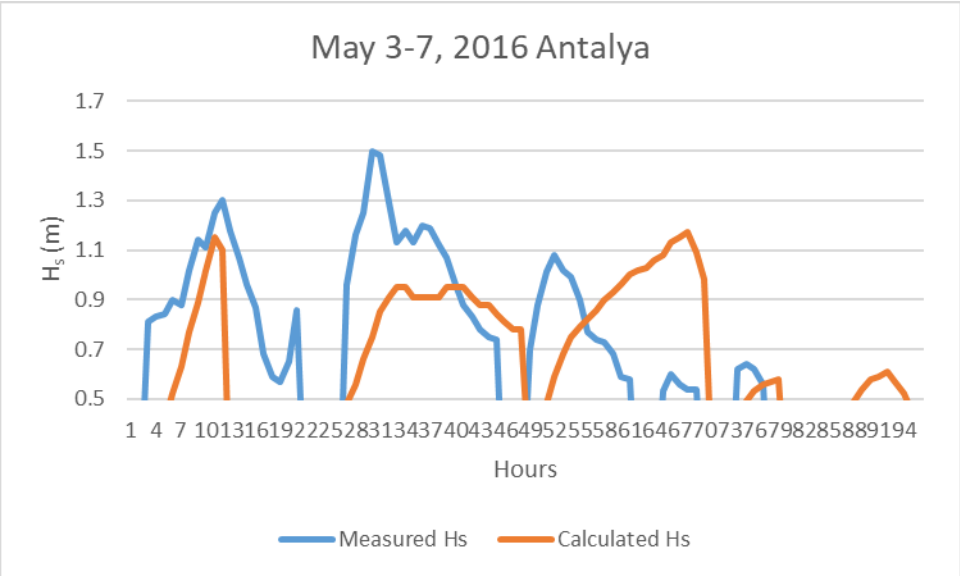

Figure 4-9 Antalya - Measured-Calculated Data Comparison for Storm-Based with Storm Duration Concept -1

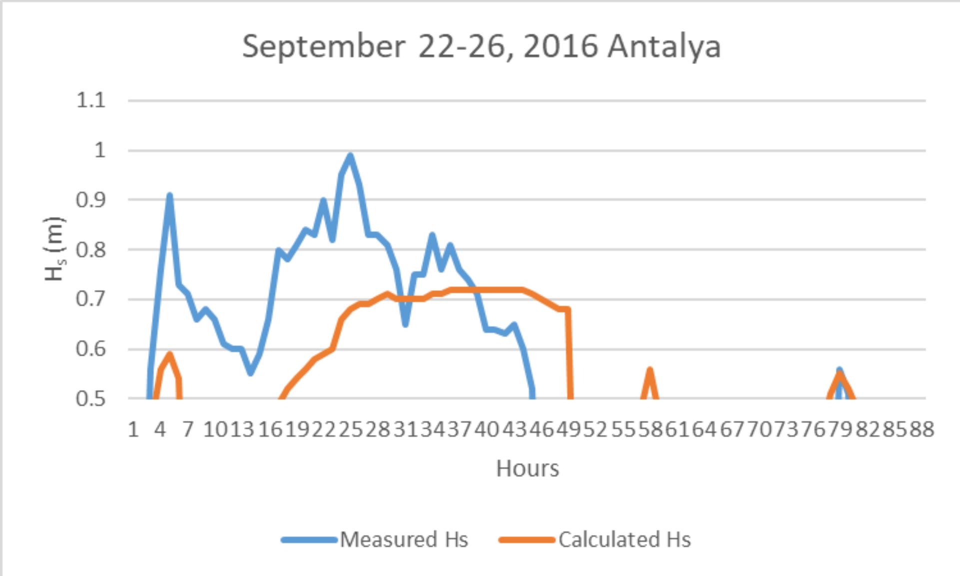

Figure 4-10 Antalya - Measured-Calculated Data Comparison for Storm-Based with Storm Duration Concept -2

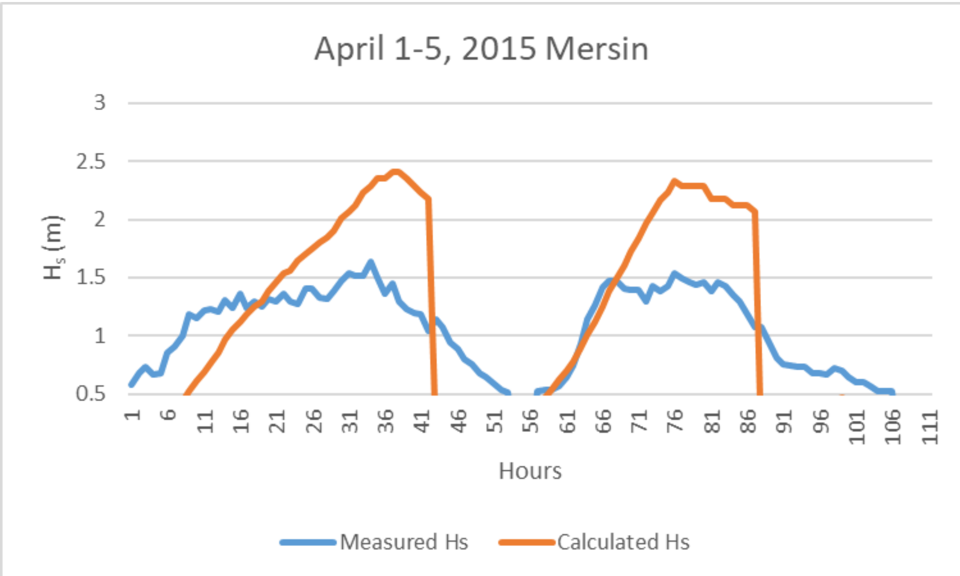

Figure 4-11 Mersin - Measured-Calculated Data Comparison for Storm-Based with Storm Duration Concept -1

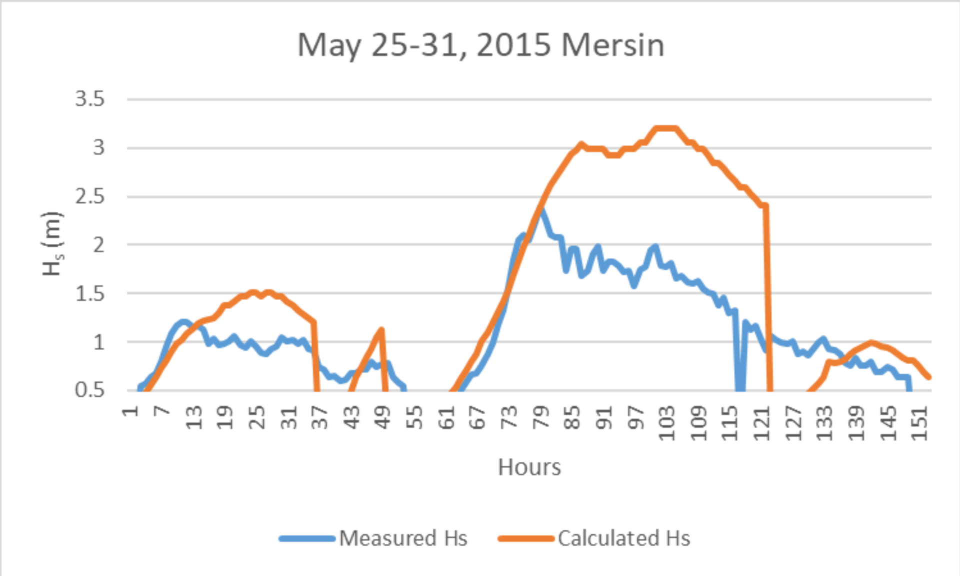

Figure 4-12 Mersin - Measured-Calculated Data Comparison for Storm-Based with Storm Duration Concept -2

4.1.4 Evaluation of Results

The studies described so far were about the calculation of significant wave height and all error calculations were also made based on calculated and measured wave height comparisons. Parametric wave prediction methods also do predictions for peak period and the developed computational tool also do calculations of peak period in a time-based way.

In order to be able to see the relation between wind speed, wind direction, wave height, peak period and also wave direction some graphs are provided in the chapters below (Chapters 4.1.4.1 to 4.1.4.4). The graphs were provided for the same two date intervals for both locations and the best conditions, resulting in minimum NRMSE. In other words, Storm-Based with User-Defined Duration concept was used with storm conditions given in Table 4-11 and 6 hour and 14 hour time windows for Antalya and Mersin, respectively. Graphs have been reviewed and some comments have been made on the graphs at both locations for the graphs.

4.1.4.1 Review of Storms in Antalya on 3-7 May 2016

Figure 4-13, Figure 4-14, Figure 4-15, Figure 4-16 and Figure 4-17 below are wind speed, wind direction, wave height, wave period and wave direction graphs, respectively based on measured and calculated data from Antalya buoy between the dates May 3 to 7 2016.

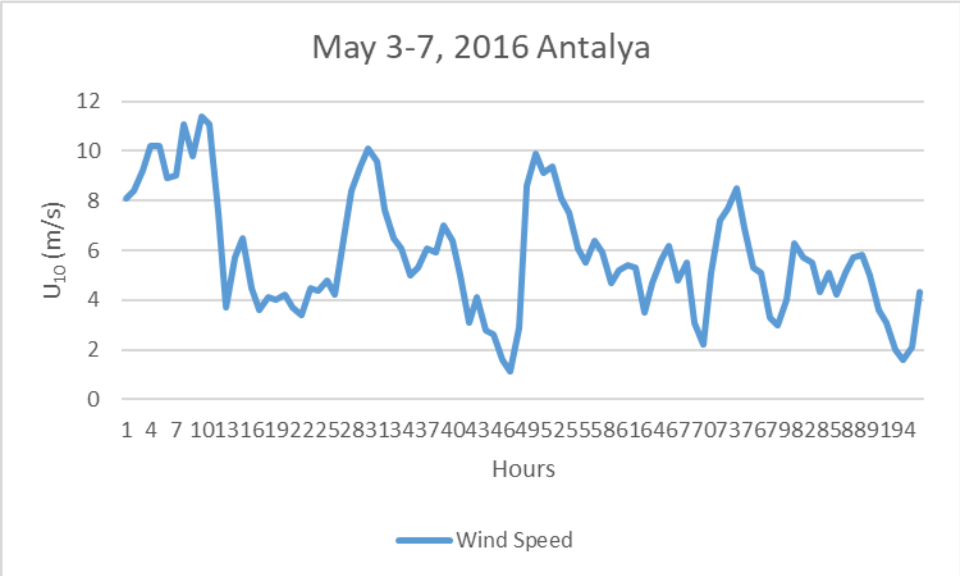

Figure 4-13 Wind Speed, Antalya 3-7 May 2016

The wind speed graph Figure 4-13 shows that wind speed remains between 4-10m/s except for a short period and has 4 peak points 3 of them around 10m/s and one of them is above 8m/s. Wind speed goes below the U_{min} value (3 m/s) around 45th, 70th and 80th hours. At the hours storms end and calculations start with 1 hour storm duration for the succeeding storms. Moreover, it is seen that on around 15th hour wind speed decreases around 6m/s instantly which is again considered as an ending of a storm. Around 50th hour there is another change in wind speed which is approximate 7m/s but this is an increase from a wind speed value below U_{min}, which means two of the storm conditions end the storm around 50th hour.

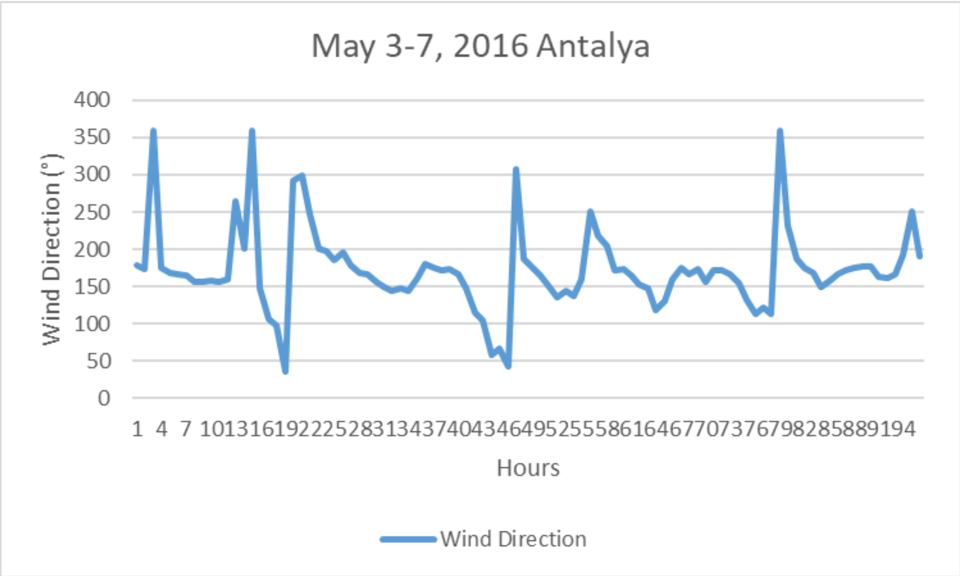

Figure 4-14 Wind Directions, Antalya 3-7 May 2016

Figure 4-14 shows the direction of the wind remains around 150°-200° except for some 3-5 hour intervals. However, during these 3-5 hour direction changes the change is almost 180°. When wind direction changes suddenly at degrees above 120° the computational tool considers the storm ends and a new storm starts which means the storm duration used in calculations will start from 1 hour again and this results in lower significant wave height values. Wind direction change at around 15th and 80th hour are sudden wind direction changes greater than 120° and these are the points where two storms were ended. It should be noted that at around 15th hour wind speed also had a sudden decrease which also ended the storm.

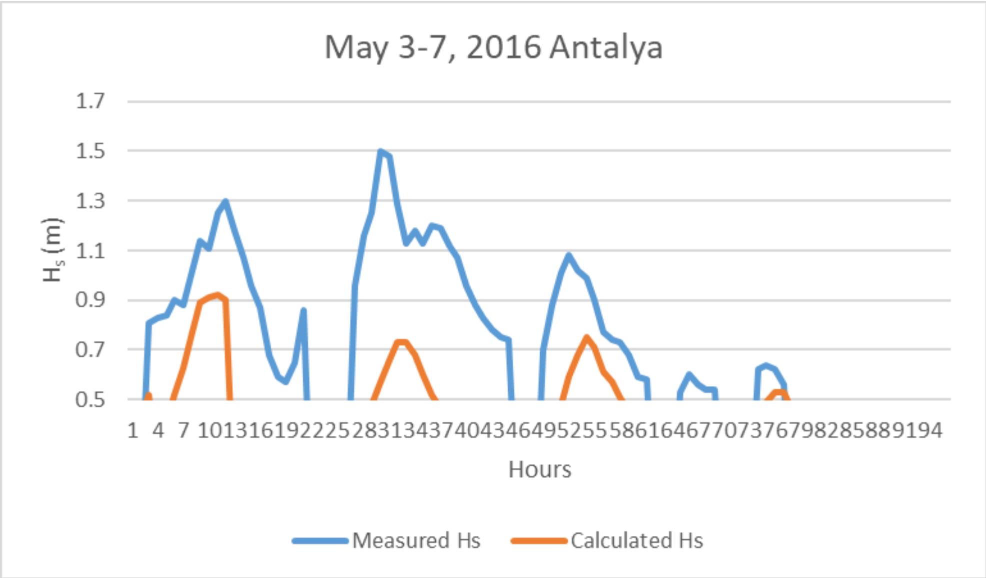

Figure 4-15 Wave Heights, Antalya 3-7 May 2016

The comparison of measured and calculated significant wave heights seen on Figure 4-15 show that calculated values were lower than the measurements. The ending of the calculated storm at 13th hour is clearly seen on the graph and this ending is compatible with instant ΔU and $\Delta\Theta$ changes at 13th hour as seen on Figure 4-13 and Figure 4-14. The measurements also show that wave height decreases below 0.5m around 20th hour, although wind speeds are above 4m/s around these hours. So, it may be interpreted that sudden wind speed and wind direction changes resulted in lower wave heights. The four wind speed peaks, seen on Figure 4-13 have resulted in four wave height peaks in both calculations and measurements. Although wind speed remains above the U_{min} value almost 90% of the given time interval it is clearly seen on Figure 4-15 that sudden wind direction and wind speed changes decreases the wave heights below 0.5m. So, it may be interpreted that, maximum wind speed change and maximum wind direction change storm conditions did not lead to better prediction of the wave heights in this particular case.

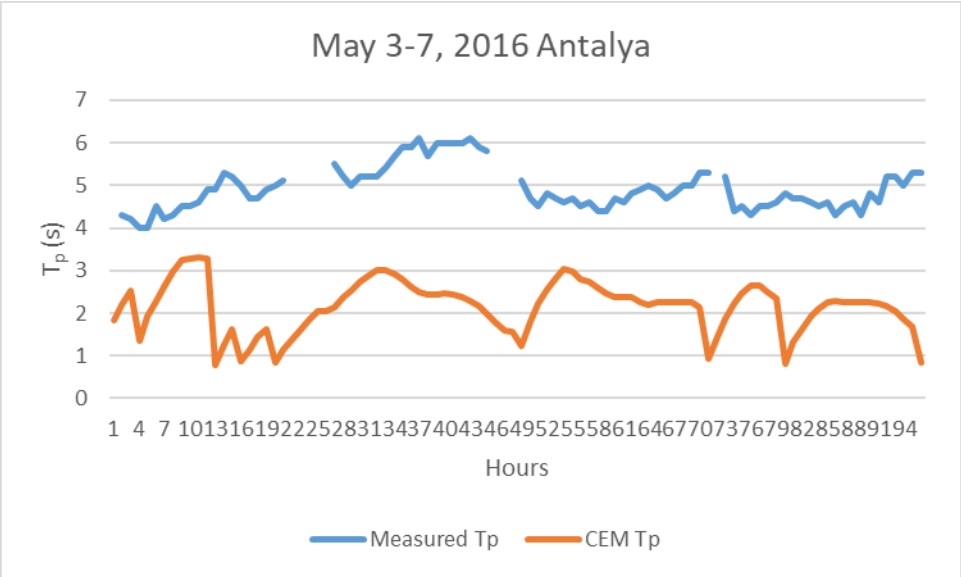

Figure 4-16 Wave Periods, Antalya 3-7 May 2016

Figure 4-16 shows that the computational tool does not give satisfactory results for wave period. Calculated values are almost half of the measured values. It should be noted that time window value and all storm conditions were determined according to the minimum NRMSE value for significant wave height. Selection of a different time window and different storm conditions may have resulted in better predictions for wave period.

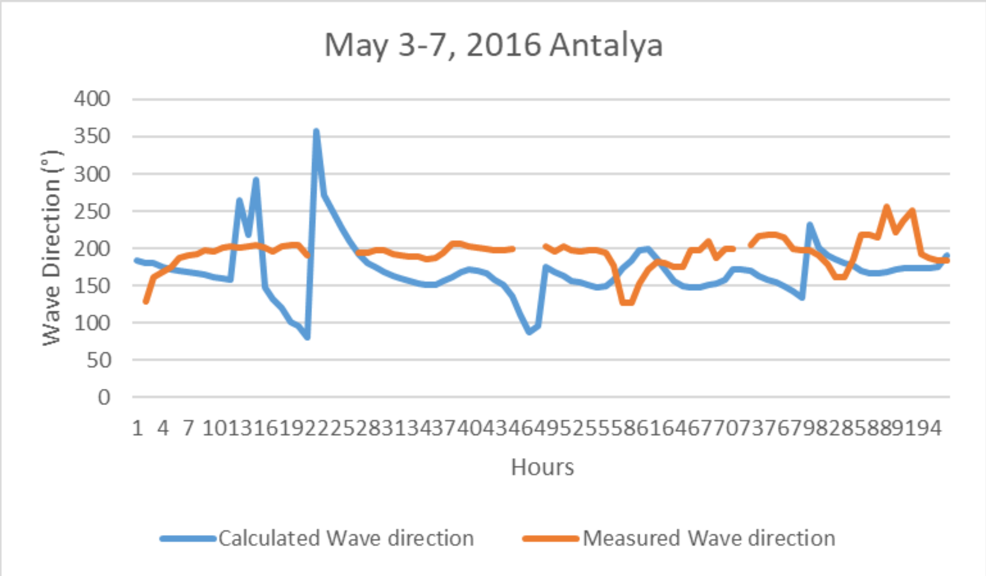

Figure 4-17 Wave Directions, Antalya 3-7 May 2016

In the calculations wave direction is taken as equal to the wind direction of every single hour. Wind directions at every hour are the average of wind directions used for the duration of the storm used for every single hour. Wind direction average is calculated with the Eq.6. When calculated wave directions are compared with buoy measurements, calculations may be considered to be compatible with the measurements except for the 10^{th}-25^{th} hour interval as seen on Figure 4-17.

4.1.4.2 Review of Storms in Antalya on 22-26 September 2016

Figure 4-18, Figure 4-19, Figure 4-20, Figure 4-21 and Figure 4-22 are the wind speed, wind direction, wave height, wave period and wave direction graphs for Antalya between the dates 22-26 September 2016.

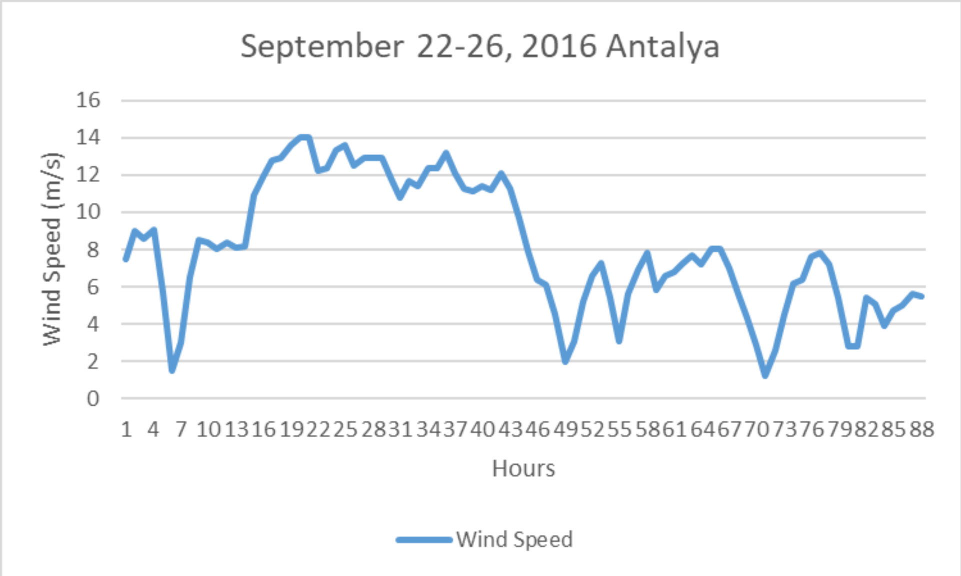

Figure 4-18 Wind Speeds, Antalya 22-26 September 2016

Figure 4-18 shows that the wind speed had the peak values around 12-14m/s around 20th to 40th hours and minimum storm wind speed condition (U_{10}>3m/s) is mostly satisfied during almost all the 88 hour shown on the graph except for three minimums around 5th, 50th and 70th hours. After around 40th hour, wind speed makes two other peaks at 8m/s.

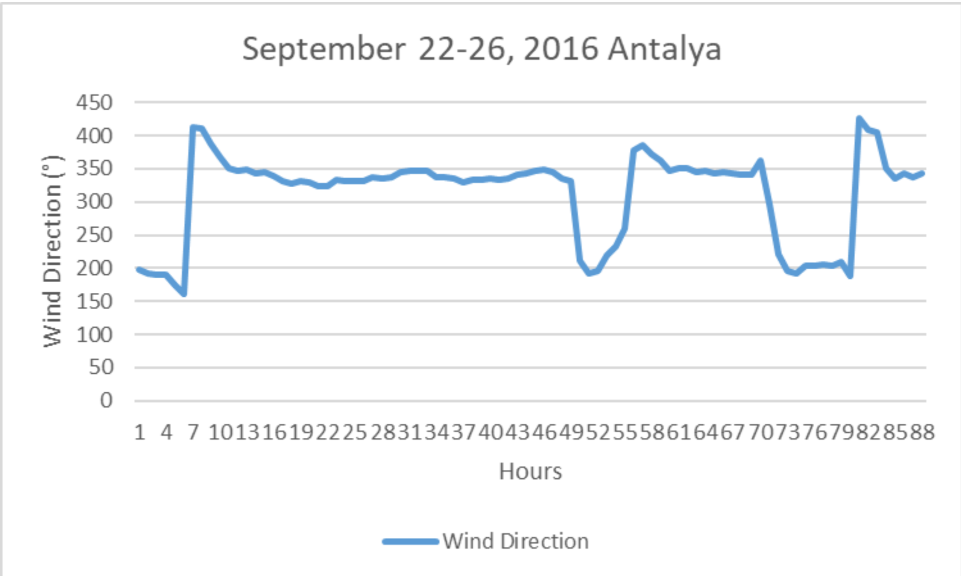

Figure 4-19 Wind Directions, Antalya 22-26 September 2016

Figure 4-19 shows that the wind direction remains in a similar direction almost all the time. It should be noted that for better representation values close to 0° were shown above 360° line. The maximum wind direction condition has ended two storms at around 50th and 70th hours. Other than that all the wind direction values are very close to each other.

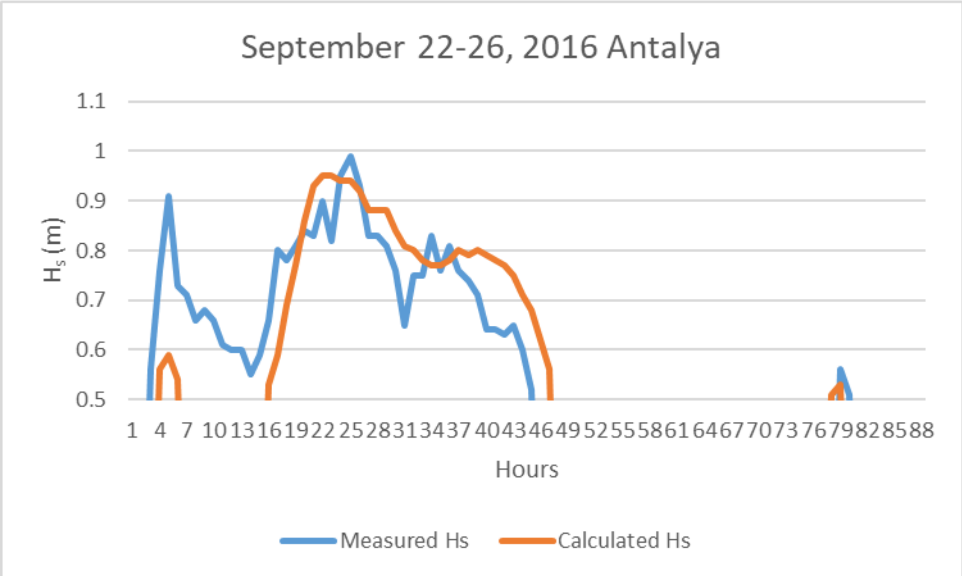

Figure 4-20 Wave Heights, Antalya 22-26 September 2016

When measured and calculated wind speeds are compared on Figure 4-20 it is seen that the calculations have resulted in satisfactory results in terms of both maximum and hourly H_s when the wind speed was around 12-14m/s. Due to the wind speed and direction change at the 5th hour (as seen on Figure 4-18 and Figure 4-19) the computational tool has considered a storm ending and according to measured wave heights apparently the storm did not end at this hour. The computational tool was also successful to predict satisfactory results for the storms after 50th hour which created a small (H_s~=60cm) two-hour peak around 80th hour.

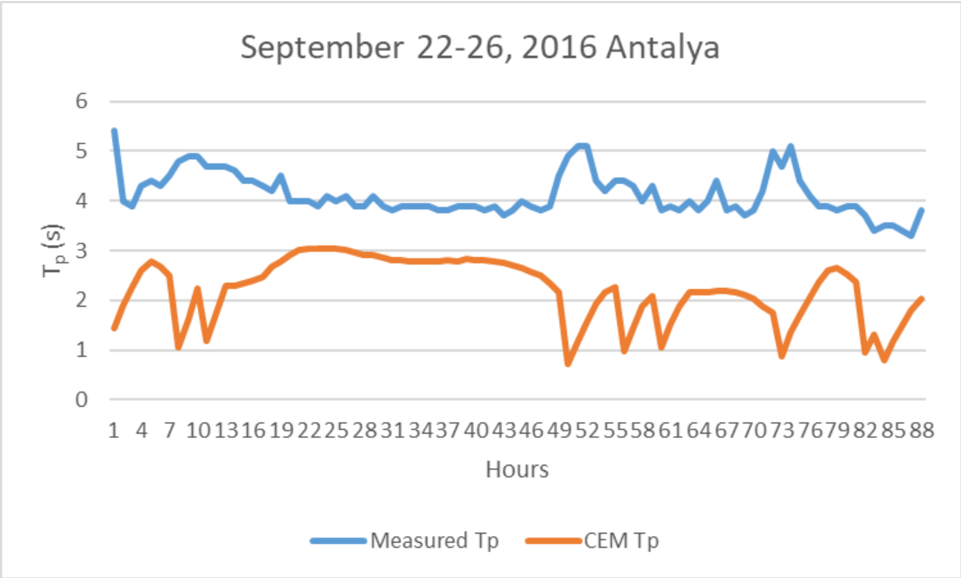

Figure 4-21 Wave Periods, Antalya 22-26 September 2016

Figure 4-21 shows the predicted wave periods are lower than the measured wave periods. Calculated periods are almost half of the measured periods. Measured periods are around 4-5s during all the data interval whereas calculated periods are between 1-3s.

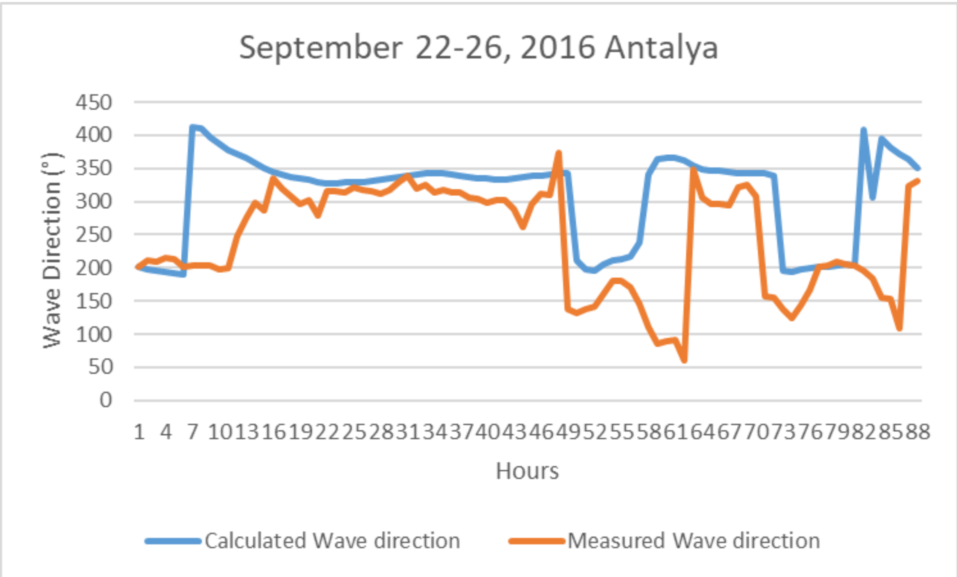

Figure 4-22 Wave Directions, Antalya 22-26 September 2016

Figure 4-22 shows that calculated and measured wave directions were compatible and the calculated wave directions, which is equal to hourly average wind direction are close to the measured wave direction values.

4.1.4.3 Review of Storms in Mersin on 1-5 April 2015

Figure 4-23, Figure 4-24, Figure 4-25, Figure 4-26 and Figure 4-27 are wind speed, wind direction, wave height, wave period and wave direction graphs for Mersin buoy between the dates April 1-5, 2015.

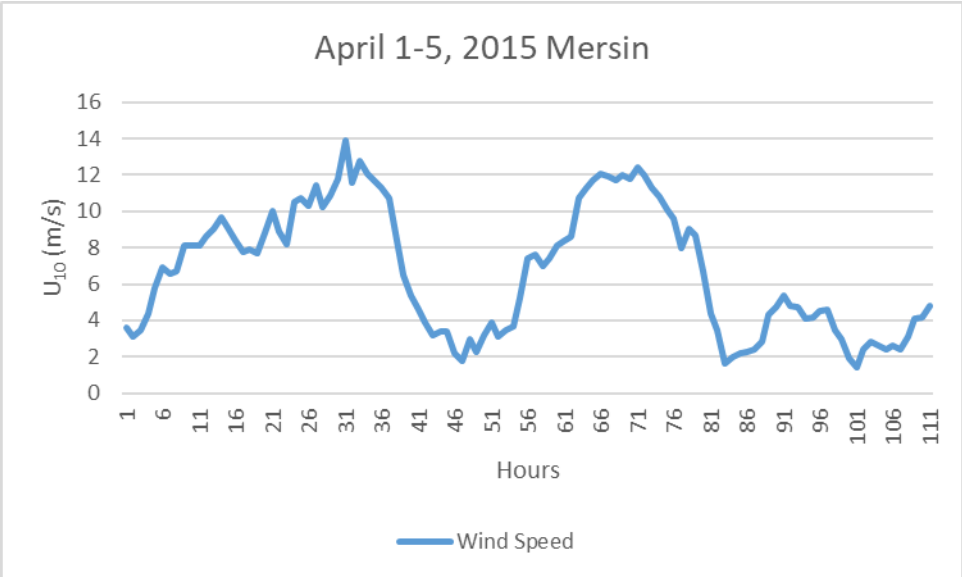

Figure 4-23Wind Speeds, Mersin 1-5 April 2015

Figure 4-23 shows that there has been two peaks around 12-14m/s during the given time interval in Taşucu, Mersin area. Wind speed has gradually increased from hour 0 to hour 35. Then it decreased below U_{min} (2.5m/s). Wind speed also decreases below U_{min} at around 80th hour and then the wind speeds are around 2-5m/s.

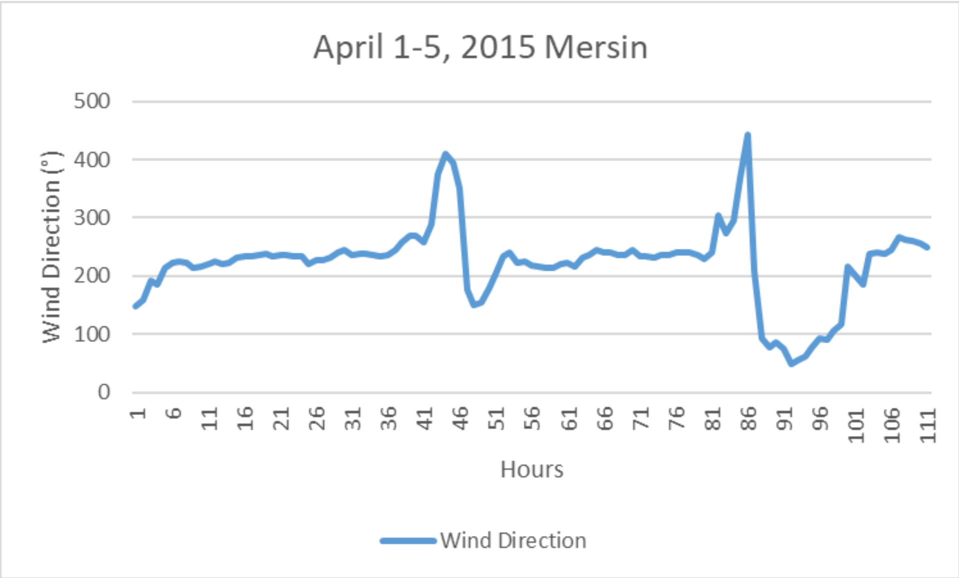

Figure 4-24 Wind Directions, Mersin 1-5 April 2015

As seen on Figure 4-24 the wind directions remain in the same direction during two peaks of wind speed and the direction values are very close to each other during these periods, i.e., between 200°-240°. Then wind direction changes when wind speed decreases below the storm condition wind speed (2.5m/s). So, the wind speed and direction graphs show two storms with similar peaks and similar and constant directions.

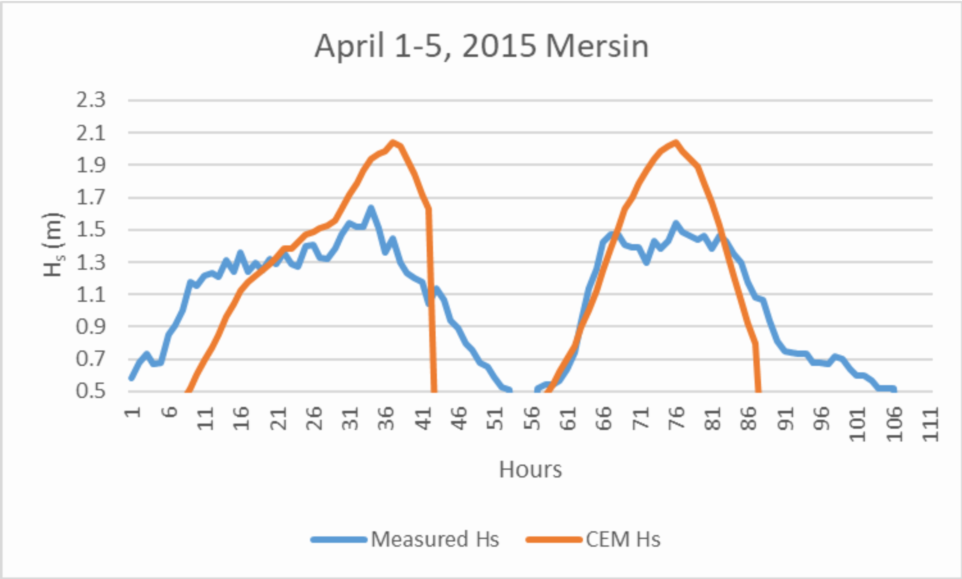

Figure 4-25 Wave Heights, Mersin 1-5 April 2015

Figure 4-25, the wave height graph, also shows two storms during this time period for both measured and calculated data. Although, the maximum calculated wave heights are slightly greater than the measured wave height, the wave height graph may be considered satisfactory considering the maximum wave heights are not too high and hourly predictions tend to have a similarity with the measured wave heights.

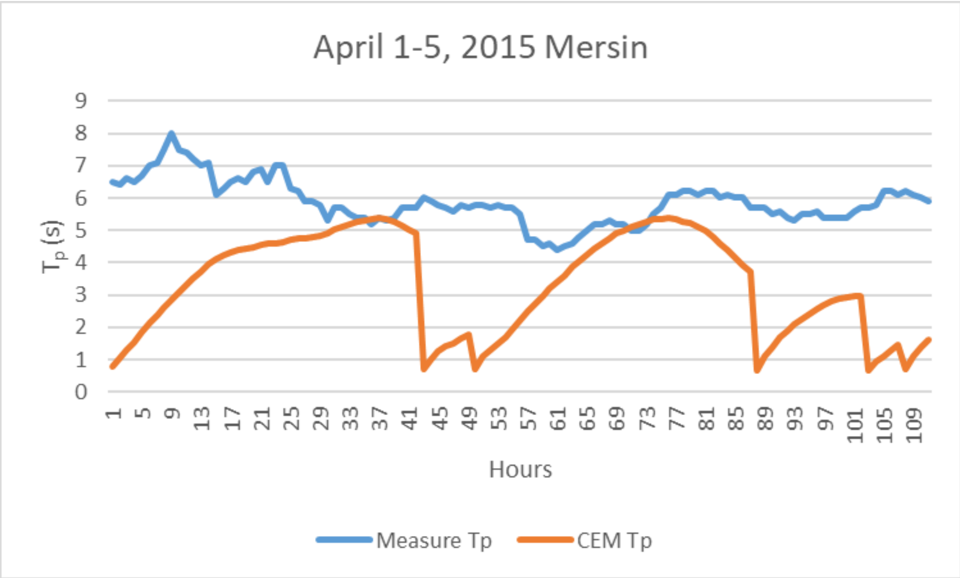

Figure 4-26 Wave Periods, Mersin 1-5 April 2015

Figure 4-26 shows that the wave periods are very smaller than the measured wave periods. It is seen that wave periods are increasing up to the peak points of wind speed and then decreasing. The peak point of the wave periods are around the peak points of wind speed and only at this point calculated wave periods are close to the measured wave periods. The measured wave periods remain in a close interval, around 5-8s, during the whole time whereas calculated wave periods are between 1-5s. The calculated wave periods reach 5s only at the peak points of wind speed.

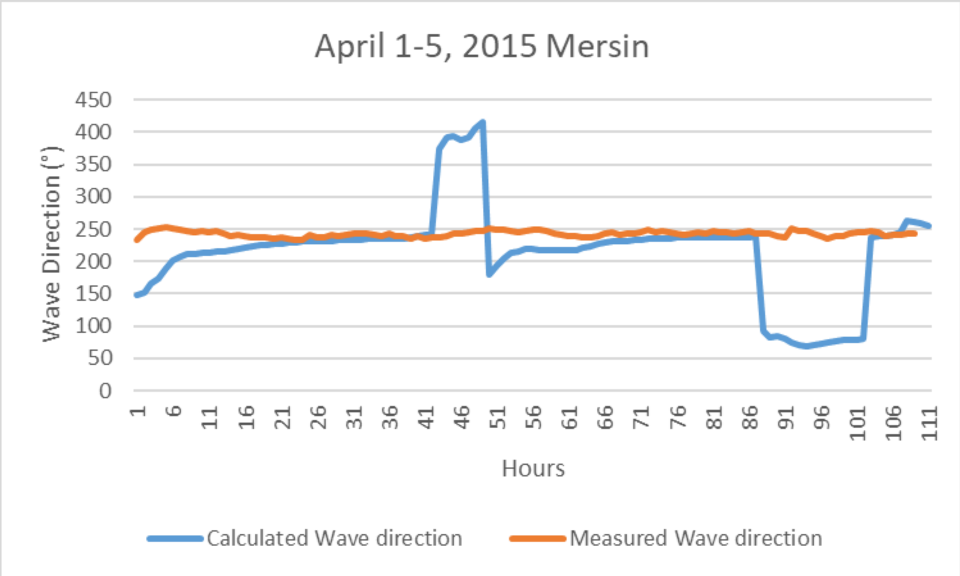

Figure 4-27 Wave Directions, Mersin 1-5 April 2015

Calculated and measured wave dimensions are very close to each other almost all the time except for 40th-50th and 85th-100th hour intervals as seen on Figure 4-27. These intervals are not storm hours and Hs values around these are below 0.5m. So, most likely the measured wave directions are swell waves from the previous storms. Since the calculation method does not take the waves from previous storms into account these wave directions are not represented on Hs graph.

4.1.4.4 Review of Storms in Mersin on 25-31 May 2015

Figure 4-28, Figure 4-29, Figure 4-30, Figure 4-31 and Figure 4-32 are wind speed, wind direction, wave height, wave period and wave direction graphs for Mersin between the dates 25-31 May 2015.

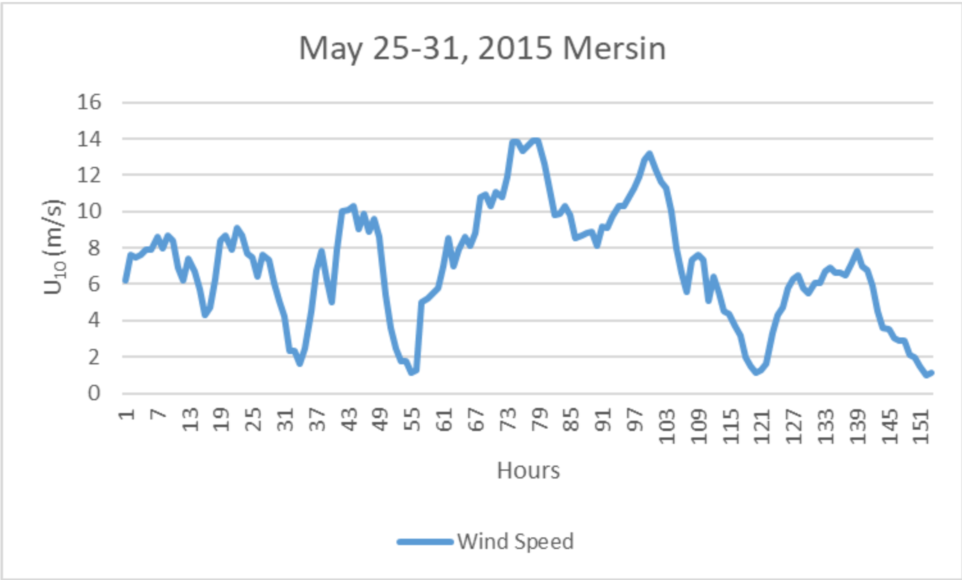

Figure 4-28 Wind Speeds, Mersin 25-31 May 2015

Figure 4-28 is the wind speed graph. The time interval starts with a storm with a wind speed around 8m/s. Then around 35th hour wind speed decreases below 3m/s, which is a storm condition. . So basically, one storm ends at this point and another storm starts around 35th hour with a peak wind speed of 10m/s. Then this storm also ends around 55th hour and a larger storm with a wind speed of 8-14m/s starts. This storm ends around 115th hour and a smaller storm with maximum wind speed of 8 m/s starts.

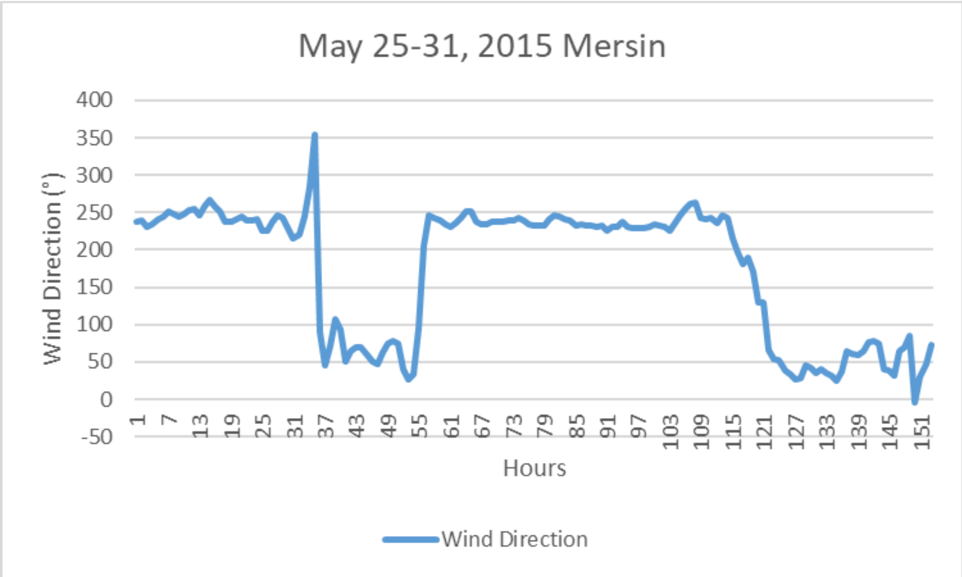

Figure 4-29 Wind Directions, Mersin 25-31 May 2015

Figure 4-29 show wind directions of Taşucu, Mersin area during the given time periods. The wind direction changes with a value greater than 45° around hour 35. So both minimum wind speed condition and maximum wind direction change condition leads to end of a storm. Wind directions show there are two main wind directions but during the storms the wind speed stays constant in small direction intervals.

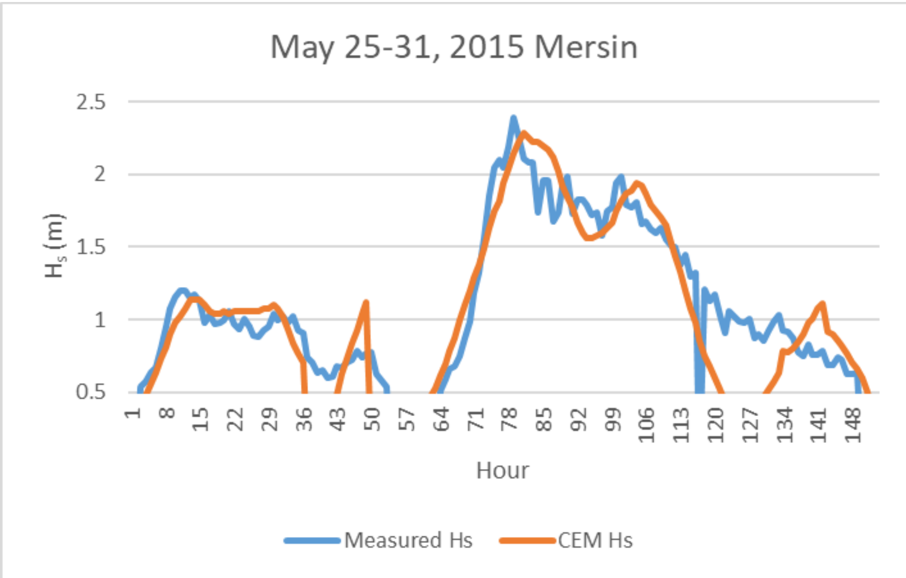

Figure 4-30 Wave Heights, Mersin 25-31 May 2015

Figure 4-30 shows the calculated and measured wave height graphs are very close to each other for all these storms. Also, when compared with the wind speed graph the wave heights have peaks at similar hours. The wind speed graph shows the results of the computational tool were very satisfactory for this location at this time interval.

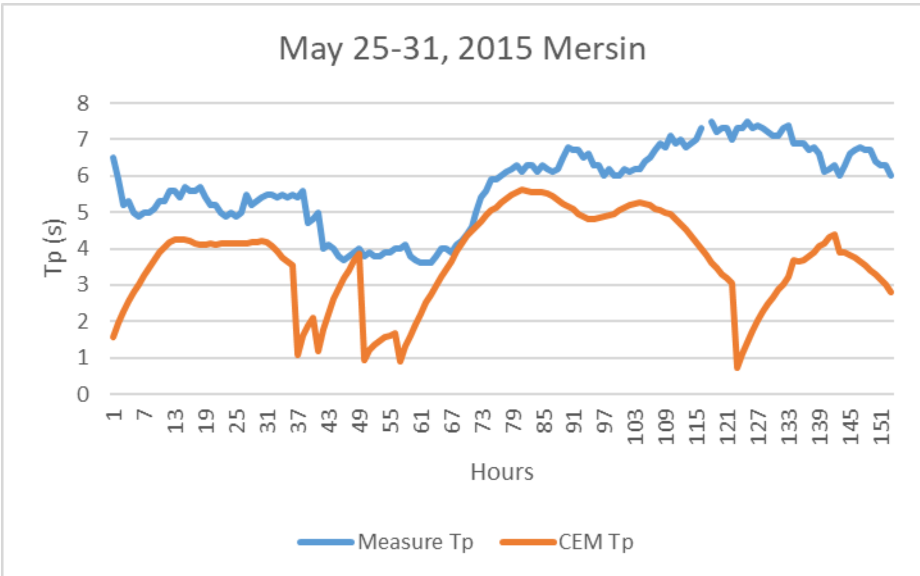

Figure 4-31 Wave Periods, Mersin 25-31 May 2015

Figure 4-31, which compares the measured and calculated wave periods, show that the calculated wave periods are much less than the measured ones. For long duration storms the peak of the calculated wave period graph reaches the measured wave period graph, however the graph clearly shows that the wave period results of the computational tool are not satisfactory to predict the wave periods.

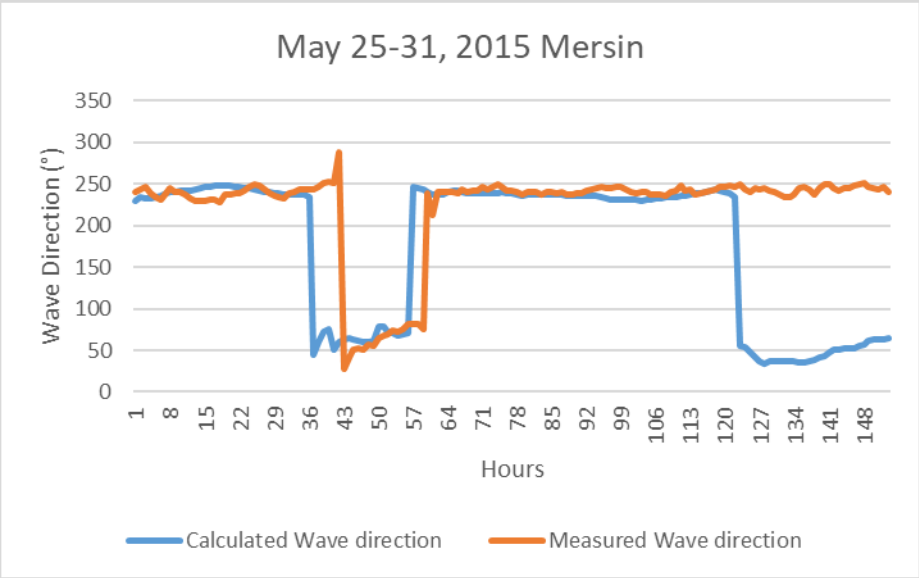

Figure 4-32 Wave Directions, Mersin 25-31 May 2015

Figure 4-32 shows the measured and calculated wave directions. It is seen that the measured and calculated values are compatible except for after the 125th hour. The wave direction after 125th are hour are compatible with the wind directions seen on Figure 4-29 at the same hours. Moreover, measured wave heights on Figure 4-30 shows a decay of wave heights at these hours whereas calculated wave heights have ended a storm and started another. Apparently, the swell waves from the previous storm have higher wave heights and measured wave directions on Figure 4-32 belong to these waves.

4.1.5 Discussions

In this study three different storm duration concepts were used in order to use parametric wave prediction methods in a time-based way. The NRMSE and NBIAS comparisons for three methods are shown on TABLE 4-13 below.

Table 4-13 NRMSE and NBIAS values for the three concepts and two locations

	Antalya		Taşucu, Mersin	
Time Window Concept	NRMSE	BIAS	NRMSE	BIAS
Continuous Data	0.233	0.143	0.143	0.114
Storm-Based with User Defined Duration	0.214	0.144	0.115	0.107
Storm-Based with Storm Duration	0.384	-0.128	0.249	-0.054

In this study NRMSE values according to H_s, were used as the most important factor to determine the accuracy of the calculations. Whereas NBIAS can be used as an indicator of how much the calculated values are higher or less than the measured ones on average. According to Table 4-13 above, Storm-Based with User-Defined concept led to minimum NRMSE. The NRMSE values for Storm-Based with Storm Duration concept are approximately twice as much the ones for Storm-Based with User-Defined concept. Also, NBIAS values are much less and negative for both Antalya and Taşucu, Mersin, which means on average the calculated values were much higher than measured values compared to other two methods. It is apparently seen on the graphs Figure 4-5, Figure 4-6, Figure 4-7, Figure 4-8, Figure 4-9, Figure 4-10, Figure 4-11 and Figure 4-12 for Storm-Based with Storm Duration concept and Storm-Based with User-Defined concept, especially for Taşucu, Mersin, for long duration storms the calculated significant wave heights get much greater than the measured ones which leads to less NBIAS and greater NRMSE.

Comparison of storm duration concepts are shown graphically for significant wave height on Figure 4-33, Figure 4-34, Figure 4-35 and Figure 4-36 below.

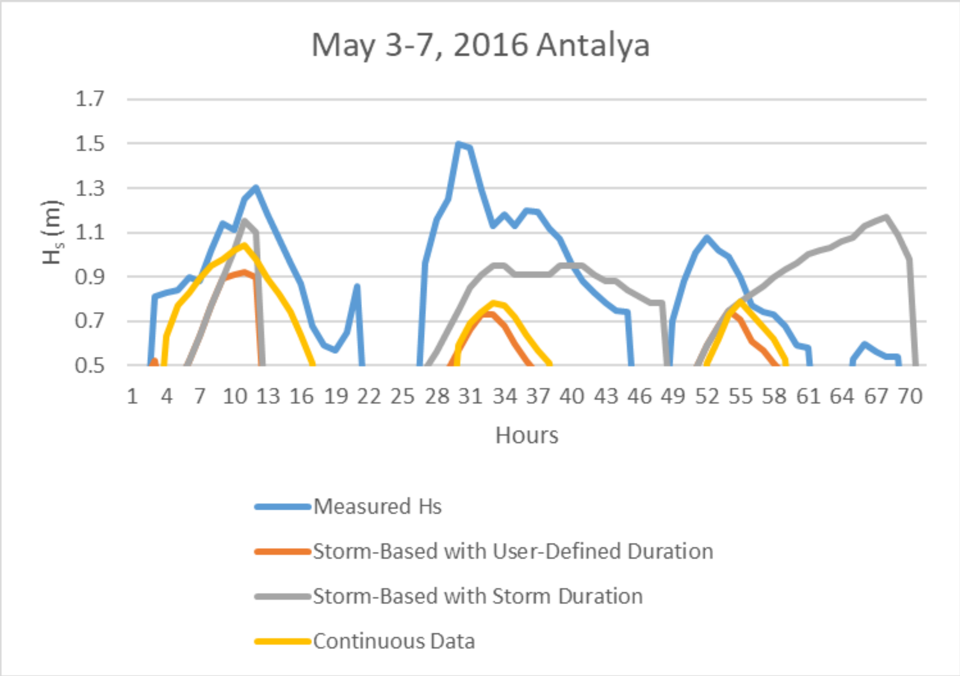

Figure 4-33 Comparison of Storm Duration Concepts Antalya May 2016

As seen on Figure 4-33 the calculated wave heights of Continuous Data concept is more close to the measured wave heights in the first 17 hours. It is apparently seen on hour 13 that adding storm conditions into the calculations has ended the first storm at 13th hour for both Storm-Based with User-Defined Duration concept and Storm-Based with Storm Duration concept. For the other two storms Continuous Data and Storm-Based with User-Defined Duration concepts have given similar results whereas Storm-Based with Storm Duration concept has resulted in higher values. Long storm durations led the Storm-Based with Storm Duration concept to give higher results.

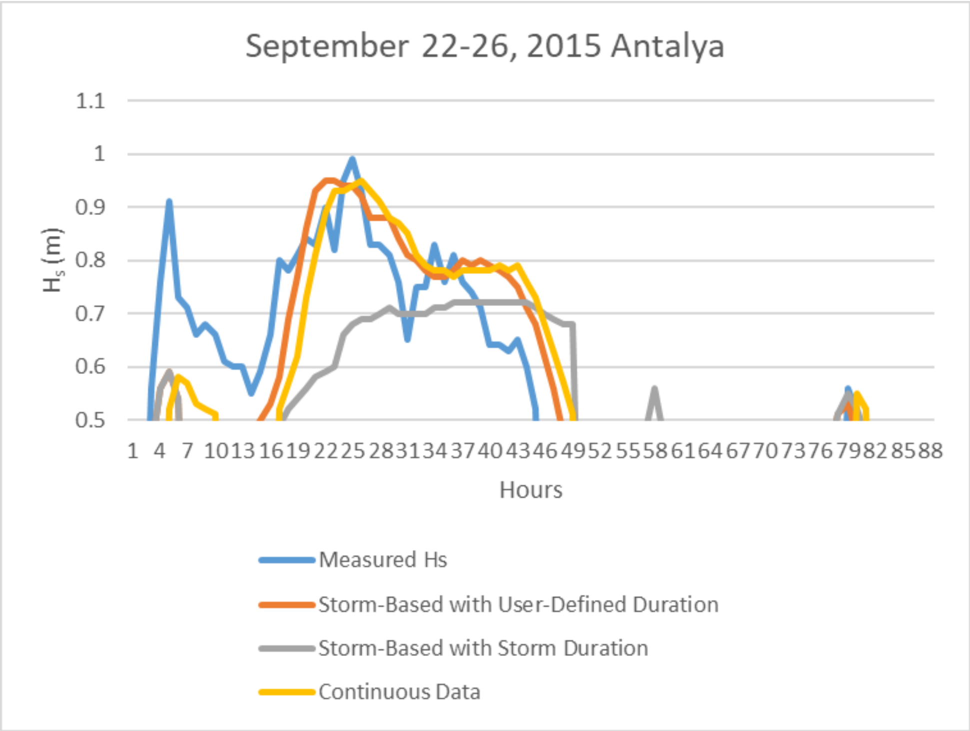

Figure 4-34 Comparison of Storm Duration Concepts Antalya September 2016

The results for Continuous Data Concept and Storm-Based with User-Defined Duration concept have resulted in very similar results in Figure 4-34 for the first 50 hours. It is understood that the long storm duration this time led to lower average wind speed values for Storm-Based with Storm Duration concept and the results lower than the measured values.

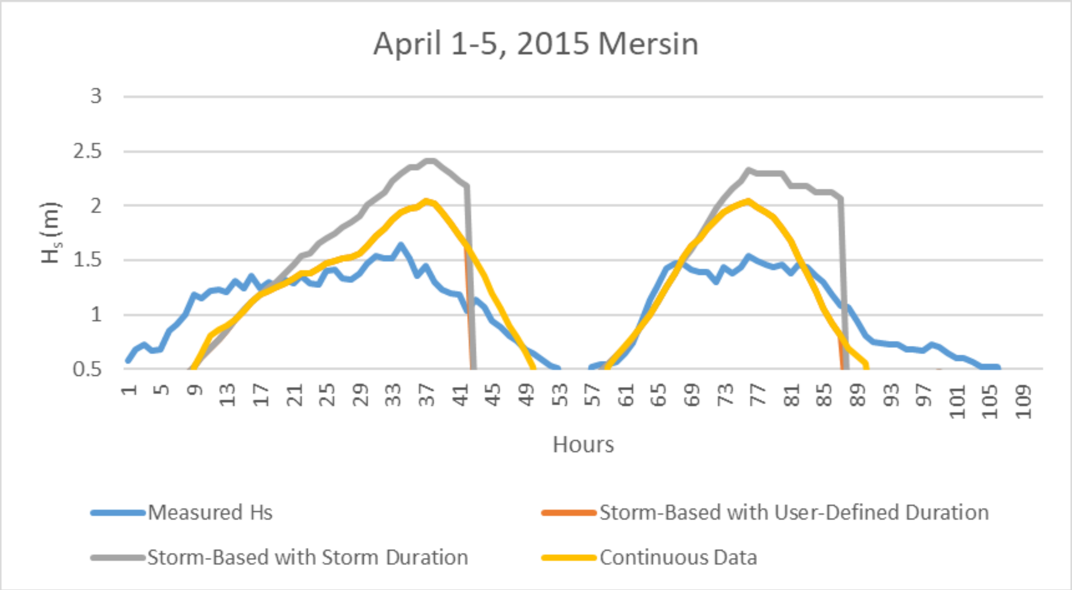

Figure 4-35 Comparison of Storm Duration Concepts Mersin April 2015

The results for Continuous Data Concept and Storm-Based with User-Defined Duration concept are almost the same on Figure 4-35. It should be noted that at 42nd hour there is a storm ending for both storm-based concepts. The Storm-Based with User-Defined Duration concept results are not visible on the graph since the results are almost same with Continuous Data concept up to 42 hour and then the storm ends for both storm-based concepts. With all storm duration concepts the maximum predicted wave height values were greater than the measured wave heights at the peak points. However, calculations for Storm-Based with Storm Duration concept resulted in higher values.

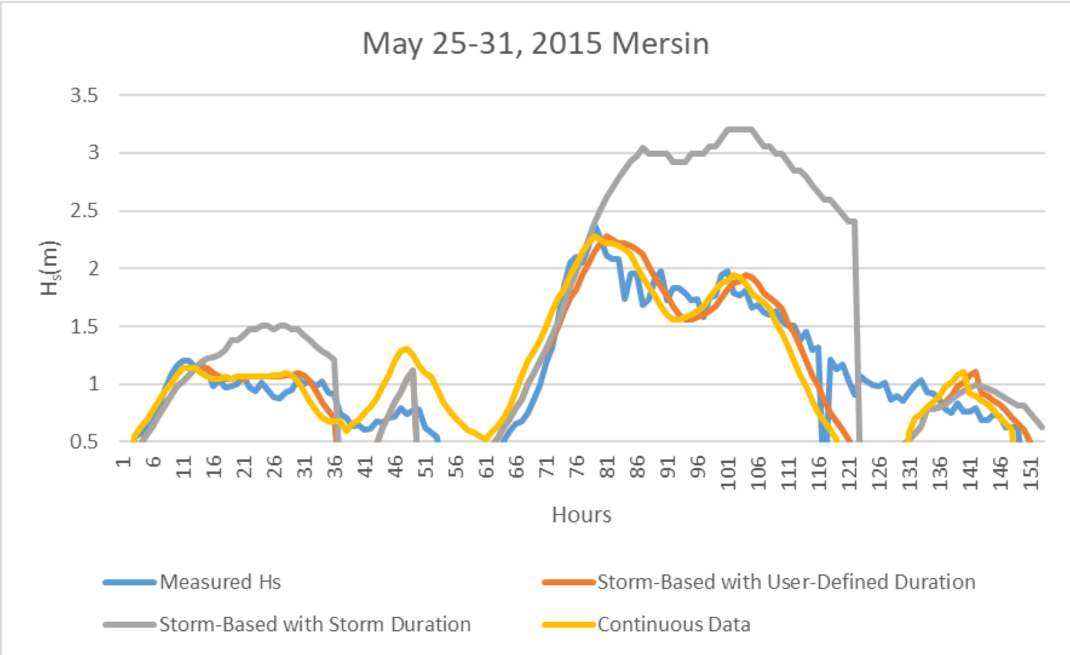

Figure 4-36 Comparison of Storm Duration Concepts Mersin May 2015

Figure 4-36 shows the results for Continuous Data concept and Storm-Based with User-Defined Duration concept are very close to measured values where as the results of Storm-Based with Storm Duration concept are much more greater than measurements.

The comparison between storm duration concepts shows that when calculations are done with a user defined time window value the results get closer to the measured data. Storm-Based with Storm Duration concept leads to errors when storm durations are very long. It is understood that, the wind speeds of very long hours ago may not have a significant effect on wave heights. Even without considering the storm conditions if a good time window value is selected satisfactory time-based predictions may be made with Continuous Data concept. However, the best NRMSE value was obtained with Storm-Based with User-Defined Duration concept and the calculation results gets closer to measured values when storm conditions are added to the equations.

Although, introduction of storm conditions to the equations led to lower NRMSE values, the change of NRMSE values for different storm condition selections were not very significant. For example in Mersin ΔΘ values between 15° to 135° led to NRMSE values between 0.115 and 0.135. The 0.02 NRMSE difference may not be considered to be satisfactory to have outcomes based on ΔΘ values. It should also be noted that a similar study shows higher differences for different ΔΘ values (Şahin C., et al., 2007). This difference may be due to the storm climate and fetch length differences of different locations studied.

One of the most important factors to use these time window concepts is selection of correct time window and storm conditions. In Antalya and Taşucu, Mersin the time window and storm conditions leading to minimum NRMSE are different from each other for both locations. In this study, these values were determined by calculating the NRMSE for these locations based on existing data. In the cases where existing data is not available this cannot be done. However, when wind data at a location exists, the storm properties tables and histograms (as described in Chapter 3.5.1) may give some information about the storm climate of the region. Fetch lengths of the location and angular interval between long fetch directions will also be known. Some of storm properties and determined best time window and storm conditions are given in Table 4-14 and Table 4-15 below for Antalya and Taşucu, Mersin. Some relations between these two tables may be developed in further studies.

Table 4-14 Storm properties of Antayla and Taşucu, Mersin

	Antalya	Taşucu, Mersin
Average Wind Speed of Storms (m/s)	5	5.2
Average Duration of Storms (h)	7.6	9.1
Average of Maximum Wind Direction Change in Storms (°)	31	27
Average of Maximum Wind Speed Change in Storms (m/s)	1.4	1.4

Table 4-15 Determined Best Time Window and Storm Conditions for Antalya and Taşucu, Mersin

	Antalya	Taşucu, Mersin
Time Window (h)	6	14
Minimum Wind Speed (Umin) (m/s)	3	2.5
Maximum Wind Speed Change (ΔU) (m/s)	3.5	2.5
Maximum Wind Direction Change (ΔΘ) (°)	120	45

Moreover, Figure 4-16, Figure 4-21, Figure 4-26 and Figure 4-31 show that the proposed method is not good at predicting wave period. This may be due to the fact that time window value and storm conditions are determined based on H_s. Selection of other time window values and storm conditions may lead to better prediction of wave periods. On the other hand, for long storm durations the peak value of calculated wave period gets closer to the peak value of measured wave period. So, for wave period predictions it may interpreted that, the proposed method is not satisfactory to predict hourly wave period values but has a potential to predict a peak value for wave period.

CHAPTER 5

CONCLUSION

Parametric wave prediction methods are used for predicting the significant wave height and corresponding peak period generated by a storm. In this study, a computational tool was developed which uses parametric wave prediction methods in a time-based manner and the developed computational tool was run with different approaches to identify hourly storm durations. Although, there are more accurate methods to determine properties of waves generated by storms in a time-based manner, using parametric methods may be an easier and faster alternative especially for feasibility studies and preliminary engineering designs. The results of the proposed storm duration concept with storm-based calculations may be considered satisfactory for some engineering needs. However, in order to use the proposed method the user should first determine a time window value and should also define the storm conditions in terms of minimum wind speed, maximum wind direction change and maximum wind speed change.

The computational tool developed in this study was developed on Visual Basic. It makes the calculations based on the time window value and storm condition parameters input by the user. It was designed for data with a time resolution of one hour and gives output with the same time resolution. The parametric wave prediction method used in this study is Coastal Engineering Manual method. However, the developed computational tool has the capacity to do calculations with all three methods described in Chapter 2.1 according to user’s selection. All these methods are in the form of functions based on storm duration, fetch length and average wind speed and giving the significant wave height and corresponding peak period and direction as output. The developed computational tool creates tables that allow the user to see all these three input values and output values at every hour of calculation. It also makes error calculations and gives NRMSE and NBIAS values when measured wave data exists and a comparison of measured and calculated values is desired. The computational tool also creates a storm properties table which gives detailed information like storm duration, average wind speed, maximum wind speed, minimum and maximum wind direction etc. about every storm as shown on Table 3-4.

The studies with existing data for Antalya and Taşucu, Mersin resulted in different time window values and different storm conditions which were found based on NRSME values. This difference may be due to the difference in storm climates of the region and difference in fetch lengths in different directions of the location. For example the angular intervals between long fetch lengths may be an indicator for the maximum wind direction change condition of a storm. Or if existing wind speed data of a region shows rapid high changes in the wind speed or directions this may again give an idea about how the storms should be defined in terms of the maximum wind speed (ΔU) and direction ($\Delta\Theta$) changes. The measured wind speeds may also give an idea about the minimum wind speed condition for defining storms.

When angular intervals for two buoys in Antalya and Mersin are compared for fetch lengths, it is seen on Figure 2-1 and Figure 2-2 that Antalya has a 90° interval where fetch lengths are greater than 200km and in Mersin there is only 45° interval where fetch lengths are greater than 200km. It is seen on Table 4-15 that the best $\Delta\Theta$ values for Antalya and Mersin are 120° and 45°, respectively. So, there may be a correlation between the angular intervals with high fetch lengths and $\Delta\Theta$ storm condition. Also, average storm duration in Antalya and Mersin are 7.6 and 9.1 hours respectively according to the Table 4-14 and best time window values were 6 hours and 14 hours for these locations which may show a correlation between average storm durations in the location and the best time window value.

When NRMSE values are compared for studied values of time window and storm conditions, it is seen on Table 4-3 and Table 4-7 that, time window value has the most impact to obtain the minimum NRMSE. In Antalya different time window selections lead to NRMSE values between 0.239-0.405 and in Mersin 0.127 to 0.492. Whereas storm conditions do not have too much impact on changing the NRMSE values. For example in Antalya minimum wind speed condition values between 2m/s to 5m/s lead to 0.222-0.239 NRMSE, ΔU condition values between 1m/s to 4m/s lead to 0.216-0.275 NRMSE and ΔΘ condition values between 15°-135° leads to 0.214-0.229 NRMSE values. In Mersin, U_{min} selections between 2m/s to 5m/s lead to 0.125-0135 NRMSE, ΔU condition values between 1m/s to 4m/s lead to 0.117-0.180 NRMSE and ΔΘ condition values between 15°-135° lead to 0.115-0135 NRMSE values. The results show that selection of time window value may change the NRMSE significantly compared to three storm conditions.

Moreover, some parametric wave prediction methods recommend the methods to be used on certain fetch lengths. This condition may also be considered and the most suitable parametric wave prediction method shall be used at different locations. In this study it is concluded that Storm-Based with User-Defined Duration concept gives the minimum NRMSE and may result in satisfactory results for some engineering needs for time-based wave predictions. It is understood that if a time window value is not defined and the calculations are made with storm duration at every time segment the calculations lead to less accurate results as storm duration increases. This may be due to the fact that wave heights at a certain time are not effected that much from the wind speeds which took place very long hours ago.

It should also be noted that determining storm properties and then determining best time window and storm conditions process is an iterative process as defined storms and their properties will change when the storm conditions are changed and without wave measurements best time window and storm conditions may not be determined. So, in order to use the proposed model, further studies are required in order to make a correlation between storm climate and fetch lenghts of an area, and the time window and storm conditions to be selected.

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