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Research Article

Numerical Modelling of Sea Storms Occurred over the Black Sea

Karadeniz'de Meydana Gelmiş Deniz Fırtınalarının Sayısal Modellenmesi

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Abstract

The objective of this study is to use numerical wave models to predict the extreme storm conditions in the Black Sea. In the past and recent years, two historical storms (February 1979 and February 6-8, 2012) that caused significant damages along the Bulgarian coast and a historical storm (February 2003) affecting the eastern part of the Black Sea and two storms (February 1999 and March 2013) that impacted southern coast of the Black Sea occurred in the Black Sea. In this study, simulations are conducted for these past and recent storms that strongly affected the coasts of the Black Sea. For the prediction of waves occurred during these storms, the third-generation numerical wave hindcast model SWAN has been applied. The ERA-Interim and CFSR winds are used as inputs to the SWAN model for modelling of the storms. The validation of the results is made by performing comparisons against in situ measurements from two buoys (data for 1999 at Hopa and 2003 at Gelendzhik) during two storms. In addition, spatial and temporal developments of the storms are examined. According to the results obtained it is seen that SWAN model using the CFSR wind fields performed better than SWAN model with ERA Interim winds and, among the used combinations, it is determined that the combination including Komen formulation for wind growth and Janssen formulation for whitecapping with whitecapping coefficient (C_{ds}) equaling to 1.5 (Komen & Janssen C_{ds}= 1.5) is the best.

Keywords: Black sea, Numerical modelling, Sea storms, SWAN

Öz

Bu çalışmanın hedefi, Karadeniz'de ekstrem dalga şartlarını tahmin edebilmek için sayısal dalga tahmin modellerini kullanmaktır. Geçmişte, Bulgaristan kıyıları boyunca belirgin hasarlara neden olan iki tarihsel fırtına (Şubat 1979 ve Şubat 6-8, 2012), Karadeniz'in doğu bölgesini etkileyen tarihsel bir fırtına (Şubat 2003) ve Karadeniz'in güney kıyılarını etkileyen iki fırtına (Şubat 1999 ve Mart 2013) meydana gelmiştir. Bu çalışmada, Karadeniz'in kıyılarını güçlü bir şekilde etkilemiş bu fırtınaların sayısal modellenmesi için analizler yürütülmüştür. Üçüncü nesil sayısal dalga tahmin modeli SWAN, bu fırtınalar boyunca meydana gelmiş dalgaların tahmini için Karadeniz'e uygulanmıştır. ERA-Interim ve CFSR rüzgar alanları fırtınaların modellenmesinde SWAN modele girdi olarak tanımlanmıştır. Sonuçların doğrulaması, iki fırtına boyunca iki ölçüm istasyonundan (Hopa istasyonunda 1999 yılına ait ve Gelendzhik istasyonunda 2003 yılına ait ölçüm verileri) temin edilmiş dalga ölçümleri ile karşılaştırılarak yapılmıştır. Bunlara ilave olarak, fırtınaların alansal ve zamansal gelişimleri incelenmiştir. Elde edilen sonuçlara göre; CFSR rüzgar alanlarını kullanan SWAN modelinin, ERA Interim rüzgar alanlarını kullanan modele göre daha iyi olduğu ve geliştirilmiş kombinasyonlar arasında rüzgar artışı olarak Komen formülünü ve köpüklenme için köpüklenme katsayısı (C_{ds}) 1,5 olarak ayarlanmış Janssen formülünü içeren kombinasyonun (Komen & Janssen C_{ds}= 1.5) en iyi sonuçlara sahip olduğu belirlenmiştir.

Anahtar Kelimeler: Karadeniz, Sayısal modelleme, Deniz fırtınaları, SWAN

1. Introduction

Storms, earthquakes, and floods among others, are the world's deadliest natural phenomena. Natural disasters do not only lead to loss of human lives, but also cause to damage of infrastructure and ecosystems thereby affecting the economy since it becomes expensive to rebuild the affected areas. Governments through researchers and scientists work to foresee the time of occurrence and magnitude of this kind of events with a goal to take precautions therefore reducing damage. Some important works have been done on storms in other areas of the world e.g. North Atlantic (Ponce de Leon and Guedes Soares, 2015; Rusu et al., 2015), Northern Europe (Behrens and Günther, 2009), India (Naga Kumar et al., 2015), Europe (Anfuso et al., 2015). Ponce de Leon and Guedes Soares (2015) described the Hercules storm

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hindcast performed with the WAM model in combination with the reanalysis of NOAA/NCEP (CFSRv2) during one of the major cyclones that occurred in the North Atlantic in the last several years. They provided a description of the development of a peculiar winter season in which a number of consecutive storms took place severely beating the west of Europe. The results were validated against the network wave buoys of the Port of Authorities (Puertos del Estado) of Spain around the North Atlantic Spanish and Portuguese continental shelf showing a high correlation during the 2 months of the simulation period (1 December 2013 up to 5 February 2014). Anfuso et al. (2015) deal with the characterization and classification of storm events affecting Cadiz Gulf, i.e. the coast including Southern Portugal, SW Spain and Northern Morocco. They focused on the frequency and distribution of the different types of storms, in order to estimate their probability of occurrence. Rusu et al. (2015) predicted the extreme storm conditions felt on the West Iberian coast, in December 2013 and January 2014. They conducted simulations these recent storms developed in the North Atlantic basin that strongly affected the western coast of the Iberian Peninsula. Their system was based on the two state-of-the-art spectral phase averaged wave models, applied at various scales (WAM model at ocean scale and SWAN model at the regional and local scales forced with the reanalysis of NCEP Climate Forecast System Version 2). The results was validated by performing comparisons against in situ measurements from various buoys that allow a good coverage of the wave conditions for the entire coast. Behrens and Günther (2009) checked the operational wave forecast system running at the German Weather Service including a regional wave model for the North Sea and the Baltic Sea whether it provides reasonable wave forecasts, especially for periods of extraordinary high sea states during winter storms. They accomplished comprehensive comparisons between wave measurements and wave model forecast data for two selected extreme storm events that induced serious damage in the area of interest. They concluded that the regional wave model is able to predict extreme events as severe winter storms connected with extraordinary high waves already about 2 days in advance. The main focus in the present study is numerical modelling of some past and recent sea storms that have affected the shores of the Black sea.

2. Material and Methods

2.1. Model Setup

The wave model SWAN (Simulating WAves Nearshore) cycle III version 41.01 model was used in this study. It was run in the third generation and non-stationary mode with a time step equal to 30 minutes. Grid definitions and the recommended choices for computational grid discretization are same with the study of Akpınar et al. (2012) for the SWAN model. Setting of physical processes and their associated coefficients for application, calibration, and validation of the model was also presented in the study of Akpınar et al. (2015; 2016). The main progress focused in the calibration is whitecapping, which is primarily controlled by the steepness of the waves. In presently operating third-generation wave models, the whitecapping formulations are based on a pulse-based model (Hasselmann, 1974), as adapted by the Wave Model Development and Implementation Group (WAMDI group, 1988):

$$S_{ds,w}(\sigma,\theta) = -\Gamma \times \frac{k}{\bar{k}} \times E(\sigma,\theta) \tag{1}$$

where k is wave number and $\bar{\sigma}$ and $\bar{k}$ denote a mean frequency and a mean wave number, respectively (cf. the WAMDI group, 1988). Γ is a steepness dependent coefficient which depends on the overall wave steepness. This steepness dependent coefficient, as given by the WAMDI group (1988), has been adapted by Günther et al. (1992) based on Janssen (1991a) (see also (Janssen, 1991b)):

$$\Gamma = \Gamma_{KJ} = C_{ds} \times \left((1-\delta) + \delta \times \frac{k}{\bar{k}}\right) \times \left(\frac{\tilde{S}}{\tilde{S}_{PM}}\right)^{p} \tag{2}$$

The coefficients C_{ds}, δ, and p are tuneable coefficients, $\tilde{S}$ is the overall wave steepness, $\tilde{S}_{PM}$ is the value of $\tilde{S}$ for the Pierson-Moskowitz spectrum (Pierson and Moskowitz 1964):

$$\tilde{S}_{PM} = \sqrt{3.02 \times 10^{-3}} \tag{3}$$

2.2. Data Used

The SWAN model was forced with two different atmospheric data: Climate Forecast System Reanalysis (CFSR) and ECMWF Interim Reanalysis (ERA-Interim). At a 10 m level 1 hourly CFSR wind fields with 0.3125° spatial resolution and 6 hourly ERA-Interim wind fields with 0.25° spatial resolution were used in the model. Wave measurements were obtained from Hopa and Gelendzhik directional wave buoys within NATO TU-WAVES project (Özhan and Abdalla, 1998) for validation of the SWAN model. Hopa buoy (100 m) and Gelendzhik buoy (85 m) are located in deep water and distances from the shore are 4600 m and 7000 m, respectively. Bathymetric data were obtained from General Bathymetric Charts of the Ocean (GEBCO, 2014) at a resolution of 30 arc-seconds in both latitude and longitude.

3. Results and Discussion

3.1. Validation of the SWAN Model

The validation of the SWAN model results is made by performing comparisons against in situ measurements from two buoys (data for 1999 at Hopa and 2003 at Gelendzhik) during two storms. Simulation of the first storm is performed for first two months (January and February) to model the 1999 storm with SWAN. Time series comparison of H_{m0} and T_{m02} hindcasts from different SWAN model settings and buoy observations is presented in Fig. 1. In this case, the most suitable model combination is examined at the Hopa buoy location (41.38333° E, 41.42333° N). As seen in Fig. 1, it is found that although SWAN model setting, which is forced with the CFSR winds, using Janssen & Janssen for wind growth & whitecapping formulations with C_{ds}=3 produced close value to the peak of the storm, but it overestimated normal wave conditions. On the other hand, SWAN model setting (Akpinar et al., 2015), which is forced with the CFSR winds, using Komen & Janssen for wind growth & whitecapping with C_{ds}=1.5 simulated more consistent results than others in comparison with the buoy measurements. At the peak point of the storm H_{m0} and T_{m02} at Hopa were estimated as 5 m and 8.5 s in this study, respectively. In the study of Yüksek et al. (2000), H_{m0} and T_{m02} at the peak of the storm at the same location were estimated as 4.0 m and 8.5 s at Hopa using synoptic wind maps. However, the measurement was 5.6 m for H_{m0} and 9.3 s for T_{m02}.

Error statistics of simulated and measured H_{m0} and T_{m02} based on the different SWAN model settings' results and buoy measurements for this storm are given in Table 1. The model performances were evaluated using some statistical parameters for example correlation coefficient (r), root mean squared error (RMSE), bias, and scatter index (SI) as shown in Table 1. The r, also called Pearson's product-moment correlation coefficient, defined as

$$r=\frac{\sum_{i=1}^{N}\left((P_i-\overline{P})(O_i-\overline{O})\right)}{\left[\left(\sum_{i=1}^{N}(P_i-\overline{P})^2\right)\left(\sum_{i=1}^{N}(O_i-\overline{O})^2\right)\right]^{1/2}} \tag{4}$$

$$\overline{P}=\frac{1}{N}\sum_{i=1}^{N}P_i \tag{5}$$

$$\overline{O}=\frac{1}{N}\sum_{i=1}^{N}O_i \tag{6}$$

where O_i is the observed value, $\overline{O}$ is the mean value of the observed data, P_i is the predicted value, $\overline{P}$ is the mean value of the predicted data, and N is the total number of data. The RMSE and SI of the predicted and observed values, defined as

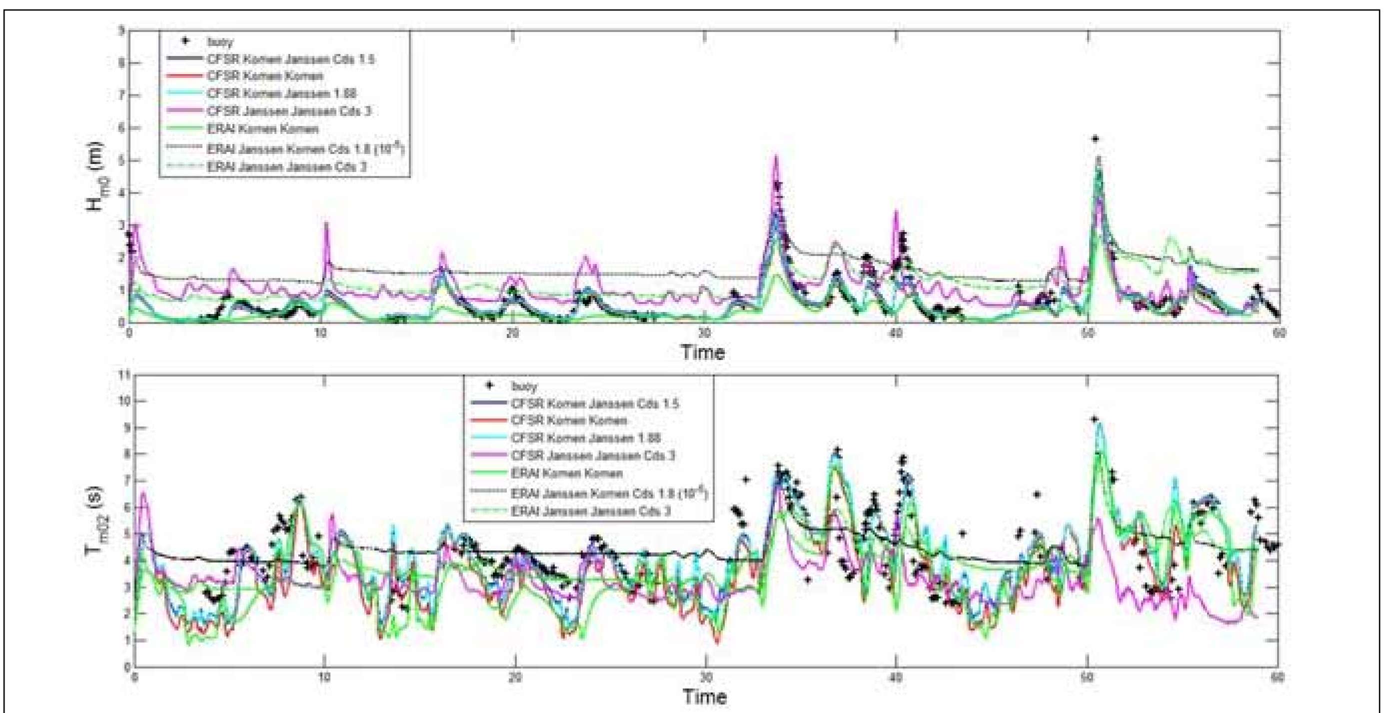

Figure 1. Time series comparison between the measurements at the buoy and the hindcast results from the different SWAN model settings during the period January 1, 1999 – February 28, 1999 at Hopa buoy location for H_{m0} and T_{m02}.

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2 \right]^{1/2} \tag{7}$$

$$SI = \frac{RMSE}{\bar{O}} \tag{8}$$

The mean bias parameter, defined as the mean of differences between predicted and observed values.

$$bias = \sum_{i=1}^{N} \frac{1}{N} (P_i - O_i) \tag{9}$$

Based on these statistics in Table 1, it can be concluded that SWAN model setting (r=0.86, SI=59%, RMSE=0.48m and bias=0.14 m for H_{m0}), forced with the CFSR winds, using Komen & Janssen combination for wind growth & whitecapping formulations with C_{ds}=1.5 provides the best performance. For T_{m02}, the same model has also the best results (r=0.63, SI=28%, RMSE=1.25 s and bias=0.039 s).

The storm affected the eastern part of the Black sea mainly the coast of Gelendzhik (37.9783° E, 44.5075° N) was selected as the second validation case. In the study of Galabov and Kortcheva (2013), it is revealed that the storm took place on the first of February and had a maximum H_{m0} of 7 m. They used the SWAN model forced with ERA Interim and ALADIN wind inputs to hindcast wave parameters of this storm. Their results show that SWAN model using ERA data underestimated H_{m0} more than 100% (it is about 3 m) while SWAN model forced with ALADIN model data underestimated it about 30% (it is about 5 m). In order to model this storm different SWAN model settings simulated over two months (January 1, 2003 to February 28, 2003) are used. And then, the present results are compared with the buoy data corresponding to the same period of time at Gelendzhik buoy location. Based on the present results SWAN model with the CFSR wind input using Komen & Janssen (C_{ds}=1.5) and Komen & Janssen (C_{ds}=1.88) for wind growth & whitecapping formulations shows the best performance. Looking at the time series, subtle differences are noted between the two settings and Komen & Janssen setting (C_{ds}=1.5) is chosen as the best model. Fig. 2 showed time series comparison between the measurements at the buoys and the hindcast results from different SWAN model settings during the period January 1, 2003 – February 28, 2003 at Gelendzhik buoy location for H_{m0} and T_{m02}. The time series of model results show an agreement with time of occurrence of the storm observed.

Table 2 shows error statistics of simulated and measured H_{m0} and T_{m02} based on the different SWAN model settings' results and buoy measurements during this storm at Gelendzhik. Based on these statistics, it can be concluded that SWAN model setting (r=0.78, SI=50%, RMSE=0.69 m and bias=0.04 m for H_{m0}), forced with the CFSR winds, using Komen & Janssen combination for wind growth & whitecapping formulations with C_{ds}=1.5 gives the better results than others. For T_{m02}, the same model has also the best performance (r=0.87, SI=20%, RMSE=0.90 s and bias=0.18 s). The measured significant wave height is 7.5 m and the mean wave period at Gelendzhik is 9.8 s.

3.2. Numerical modelling of sea storms

3.2.1. February 1979 Storm

A severe storm at Shkorpilovtsi (27.925986° E, 42.962532° N) in February 1979 was covered by Galabov and Kortcheva (2013). Belberov et al. (2009) mentioned that at 15 m water depth, a 5.8 m significant wave height (H_{m0}) during this storm was observed at Shkorpilovtsi beach. This value was calculated as 5.5 m by SWAN model forced with the downscaled wind input and 4 m by SWAN model

Table 1. Error statistics of simulated and measured H_{m0} and T_{m02} based on the different SWAN model settings' results and buoy measurements. The default values for C_{ds} are 2.36e-5 and 4.5 for Komen and Janssen formulations for whitecapping, respectively.

Wind	Wind growth formulation	Whitecapping formulation	C_{ds}	N	H_{m0}				T_{m02}			
					r	bias (m)	RMSE (m)	SI	r	bias (m)	RMSE (m)	SI
ERAI	Komen	Janssen	1.5	301	0.57	-0.44	0.82	1.00	0.40	0.53	1.43	0.32
ERAI	Komen	Komen	2.36e-05	301	0.73	0.41	0.75	0.92	0.52	0.70	1.63	0.36
ERAI	Janssen	Komen	1.80e-05	301	0.69	-0.86	1.05	1.29	0.47	-0.01	1.24	0.28
CFSR	Komen	Janssen	1.5	301	0.86	0.14	0.48	0.59	0.63	0.04	1.25	0.28
CFSR	Janssen	Janssen	3	301	0.73	-0.36	0.68	0.83	0.45	1.05	1.66	0.37
CFSR	Komen	Komen	2.36e-5	301	0.86	0.24	0.54	0.66	0.68	0.43	1.28	0.28
CFSR	Komen	Janssen	1.88	301	0.86	0.18	0.51	0.62	0.62	0.07	1.27	0.28

forced with the ERA-Interim wind input in the study of Galabov et al., (2015) and as 4 m by Galabov and Kortcheva (2013). They also mentioned that the available information about the event corresponded well with the max storm surge values although usage of the reanalysis was not successful in reproducing the intensity of the storm. In the present study, using different SWAN model settings forced with ERA Interim and CFSR wind inputs for the period of two months (January 1, 1979 to February 28, 1979), spatial and temporal variations of H_{m0} simulated during the storm can be traced, its magnitude and the period of occurrence. Due to unavailability of buoy data for this location, the SWAN

Table 2. Error statistics of simulated and measured H_{m0} and T_{m02} based on the different SWAN model settings' results and buoy measurements.

Wind	Wind growth formulation	Whitecapping formulation	C_{ds}	N	H_{m0}				T_{m02}			
					r	bias (m)	RMSE (m)	SI	r	bias (m)	RMSE (m)	SI
CFSR	Komen	Janssen	1.5	601	0.78	0.04	0.69	0.50	0.87	0.18	0.90	0.20
CFSR	Janssen	Janssen	3	601	0.73	-2.18	2.61	1.88	0.74	-1.00	1.47	0.33
CFSR	Komen	Komen	2.36e-05	601	0.78	0.19	0.69	0.50	0.87	0.41	1.07	0.24
CFSR	Komen	Janssen	1.88	601	0.78	0.10	0.68	0.49	0.87	0.20	0.92	0.20
ERAI	Janssen	Janssen	3	601	0.52	-0.05	0.88	0.64	0.65	1.05	1.61	0.36
ERAI	Komen	Komen	2.36e-05	601	0.57	0.75	1.14	0.82	0.68	1.49	1.90	0.42
ERAI	Janssen	Komen	1.8e-5	601	0.50	-0.55	1.07	0.77	0.56	0.62	1.41	0.32

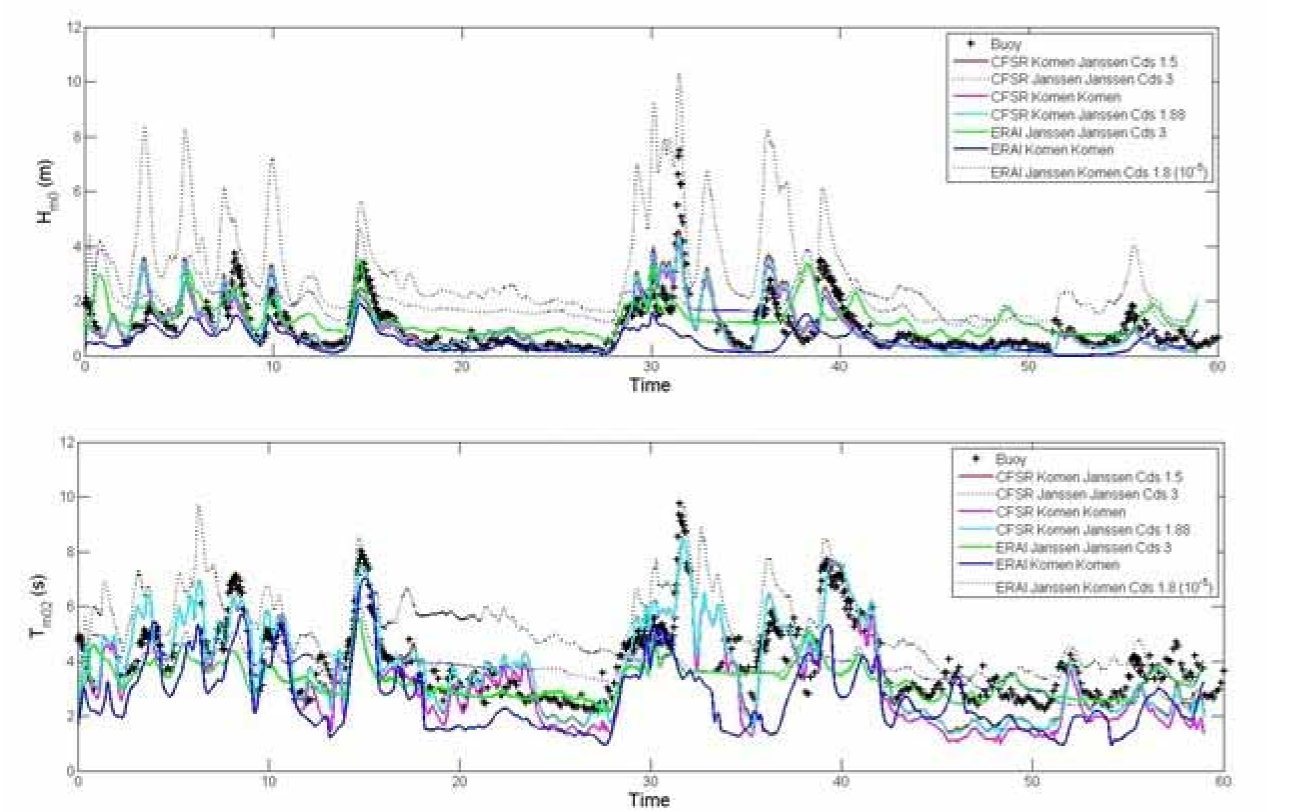

Figure 2. Time series comparison between the measurements at the buoys and the hindcast results from the SWAN model settings during the period January 1, 2003 – February 28, 2003 at Gelendzhik buoy location for H_{m0} and T_{m02}.

models' results using two wind inputs can not be compared with in-situ measurements. Based on model performance comparisons during two storms where the measurements are available in validation section of the present study above, the SWAN model, Komen & Janssen for wind growth & whitecapping formulations with C_{ds}=1.5 setting, forced with the CFSR winds is chosen as the best over the other combinations due to its better performance observed during other storms than that of other SWAN model settings.

The 1-d energy density spectrum from the best setting SWAN model at different hours at Shkorpilovtsi in the coast of Bulgaria is given in Fig. 3. It shows that the storm had a maximum value of 367 m^2/Hz on February 19, 1979, around 12:00 at the location. Also, at this location, at the peak of the storm, H_{m0} and mean wave period (T_{m02}) reached a value of 5.5 m and 8.5 s respectively. The result at Shkorpilovtski in the present study is rather close to measurement observed by Belberov et al. (2009). Besides, it is in line with the result of SWAN model forced with the downscaled wind input in the study of Galabov et al., (2015).

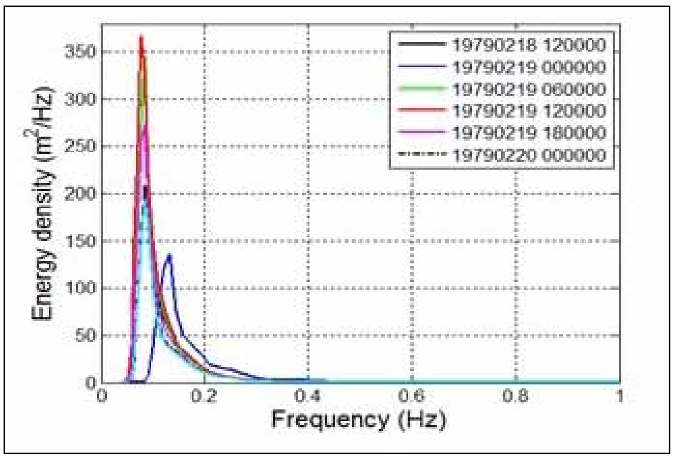

Figure 3. 1-d energy density spectrum simulated from the best setting SWAN model setting at different hours at Shkorpilovtsi.

Spatial and temporal development of simulated H_{m0} and wind speed fields from results of the best SWAN model setting forced with the CFSR winds during the storm is shown in Fig. 4. As in the figure, this storm occurred in the western part of the Black sea and ended there without affecting the eastern part. It emerged in the early hours of 18th of February, 1979 at around 03:00 am and reached its peak (8.38 m) around the same region on the 19th of February between 12:00 midnight and 03.00 am. Waves produced by winds blowing from north eastern (NE) direction in the eastern part and then in the western part east (E) direction affected the coasts of Bulgaria, Romania and north western Turkey. In this region, high speed winds of 20 m/s and above produced an H_{m0} around 8 m.

3.2.2. February 1999 Storm

1-d energy density spectrum simulated from the best SWAN model setting at different hours at Hopa is also

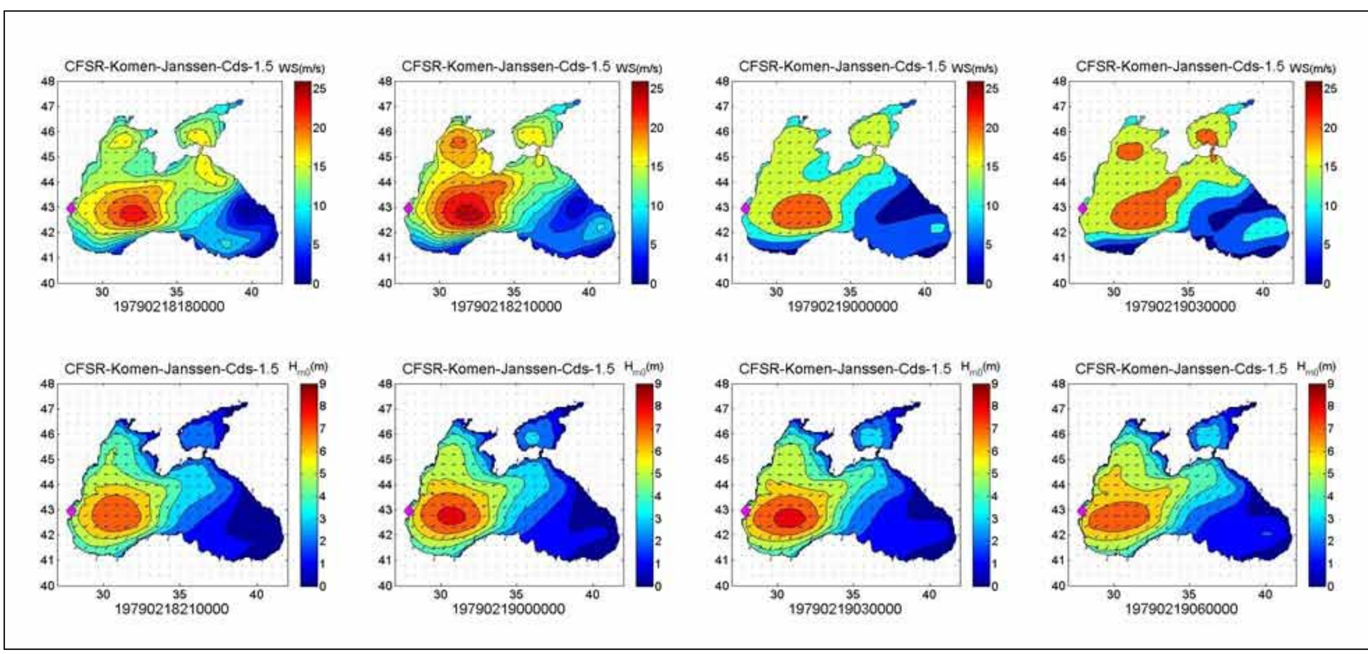

Figure 4. Spatial and temporal development of simulated H_{m0} fields and CFSR wind speed fields and wind and wave direction vectors from the best setting SWAN model simulations forced with the CFSR winds. Pink diamonds in the figures represent the Shkorpilovtsi location.

given in Fig. 5. This shows that the storm has a maximum value of 390 m²/Hz at Hopa at February 20, 1999, 15:00. Spatial and temporal development of simulated H_{m0} and wind speed fields and wind and wave direction vectors from the best setting SWAN model simulations forced with the CFSR winds during the storm are shown in Fig. 6. Here, it seems that the storm originated from north eastern part of the Black sea in the early hours of February 19, 1999, without affecting the western part, gained strength and proceeded toward the south eastern part of the Black Sea (Hopa coastal area) on the 20th of February around the hours of 12:00 to 15:00 p.m. At Hopa it is here observed that the storm caused wave heights of as much as 8 m at the open sea and about 5 m along the coast. Hopa coastal area was affected by north westerly (NW) waves produced by the winds in the same direction.

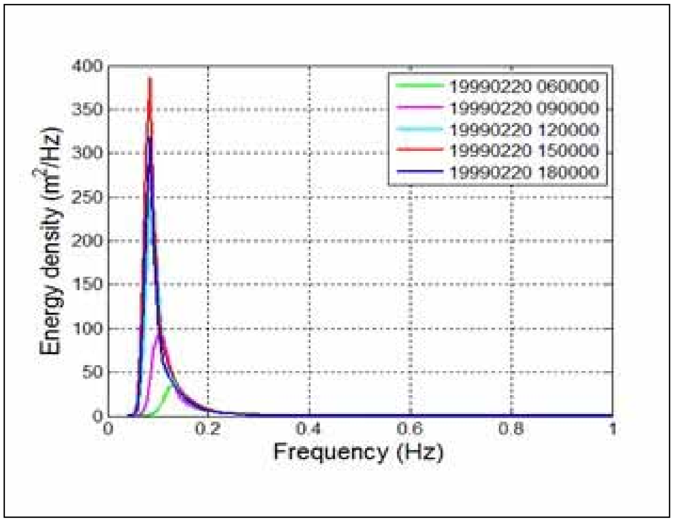

Figure 5. 1-d energy density spectrum simulated from the best SWAN model setting at different hours at Hopa.

3.2.3. February 2003 Storm

The February 1, 2003 storm seems to have originated from the western part of the Black sea in the late hours of 31st of January, 2003 and escalated towards the north-east Black Sea before reaching Gelendzhik. An energy density of about 250 m²/Hz is observed on the 1-d energy density spectrum in Fig. 7. This maximum energy density occurred at Gelendzhik on February 1, 2003, at 03:00. Fig. 8 represents spatial and temporal development of simulated H_{m0} and wind speed fields and wind and wave direction vectors from the best setting SWAN model simulations forced with the CFSR winds during the storm event. The storm had wave heights as high as 6 m produced by severe winds of speeds more than 15 m/s at open sea and 4.5 m along the coast.

3.2.4. February 2012 Storm

The 2012 storm, near the town of Ahtopol (27.96° E, 42.104644° N) in Burgas, is among the most recent ones. It occurred between 06-08 February and led to damages in the area. Galabov and Kortcheva (2013) reported that

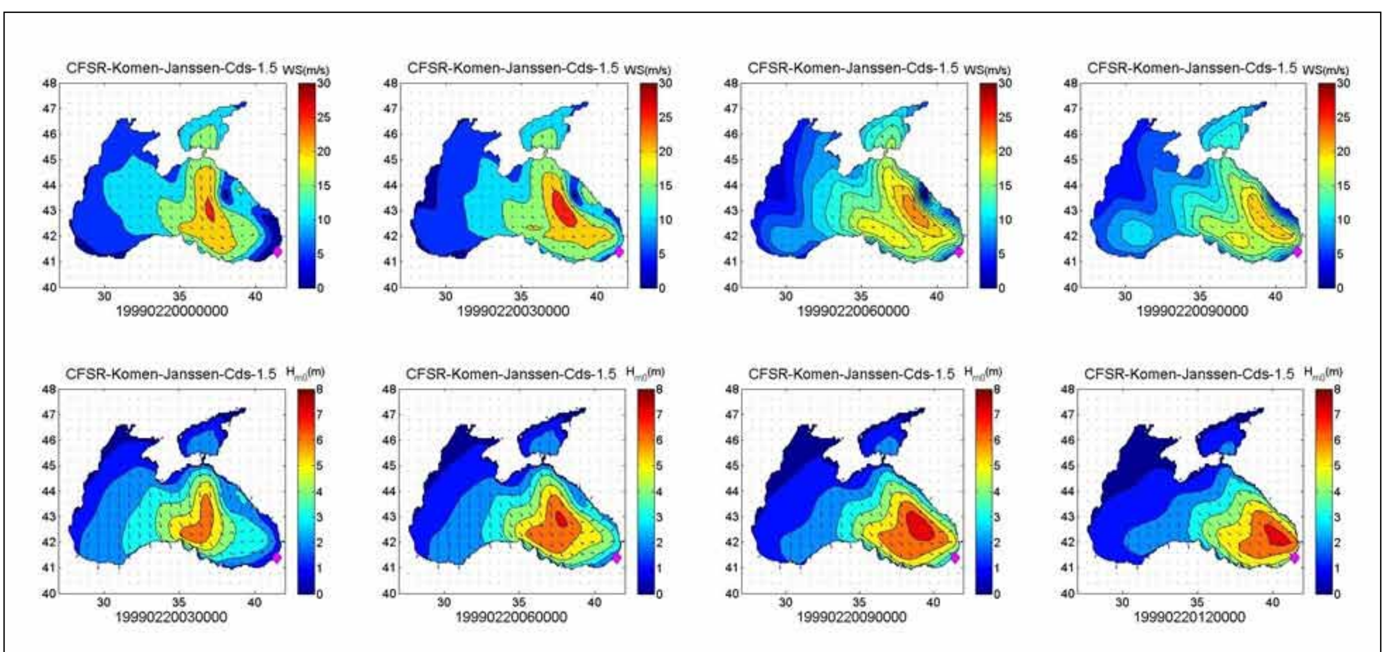

Figure 6. Spatial and temporal development of simulated H_{m0} fields and CFSR wind speed fields and wind and wave direction vectors from the best setting SWAN model simulations forced with the CFSR winds. Pink diamonds in the figures represent the Hopa location.

the satellite altimetry data and the visual observations by the coastal meteorological stations showed that significant wave heights reached 5 m. They applied SWAN model at this location using ERA-Interim and ALADIN wind inputs and found out that SWAN using the ALADIN data simulated maximum value of 4.7 m. In the present study, CFSR wind input is used and the simulated maximum significant wave height and mean wave period are 6 m and 9 s on the 8th of February, respectively. Galabov et al. (2015) stated that Pasha Dere coast was also affected during the February 2012 storm. They mentioned that according to the in-situ measurements (by ADCP) the highest significant wave height was observed 4.77 m with a peak period of 11.5 s and direction 84° at 20 m depth. With matching time of occurrence, in the present study, significant wave height was found out 5.20 m with a peak period of 12.31 s and 87° in direction.

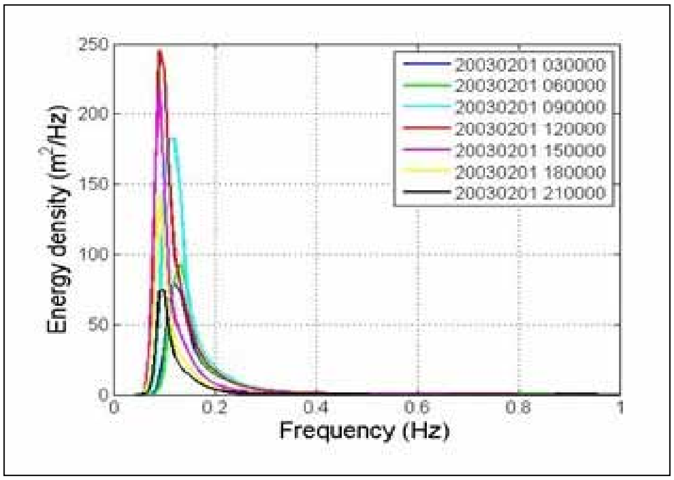

Figure 7. 1-d energy density spectrum simulated from the best SWAN model setting at different hours at Gelendzhik.

The energy density spectrum for the February storm at different hours around its peak at Ahtopol is presented in Fig. 9. The graph shows that the storm reached an energy density of 480 m^2/Hz during its peak at 03:00 am. Fig. 10 shows the beginning and the end of the storm in detail. Based on this, it is seen that the storm was created by north easterly winds and affected the southwestern part of the Black sea. It shows that there was a 6 m H_{m0} along the coast of Ahtopol and 9 m H_{m0} at open sea during the peak of the storm. Based on the spatial development in Figure 10, it is found that the storm occurred between the 6th and 9th of February.

3.2.5. March 2013 Storm

Komen & Janssen combination for wind growth & whitecapping formulations with C_{ds}=3 forced with CFSR was chosen among the other combinations due to its better performance in comparison with others proven above. Due to lack of buoy data at this location, model results could not be compared with in-situ but the development of the

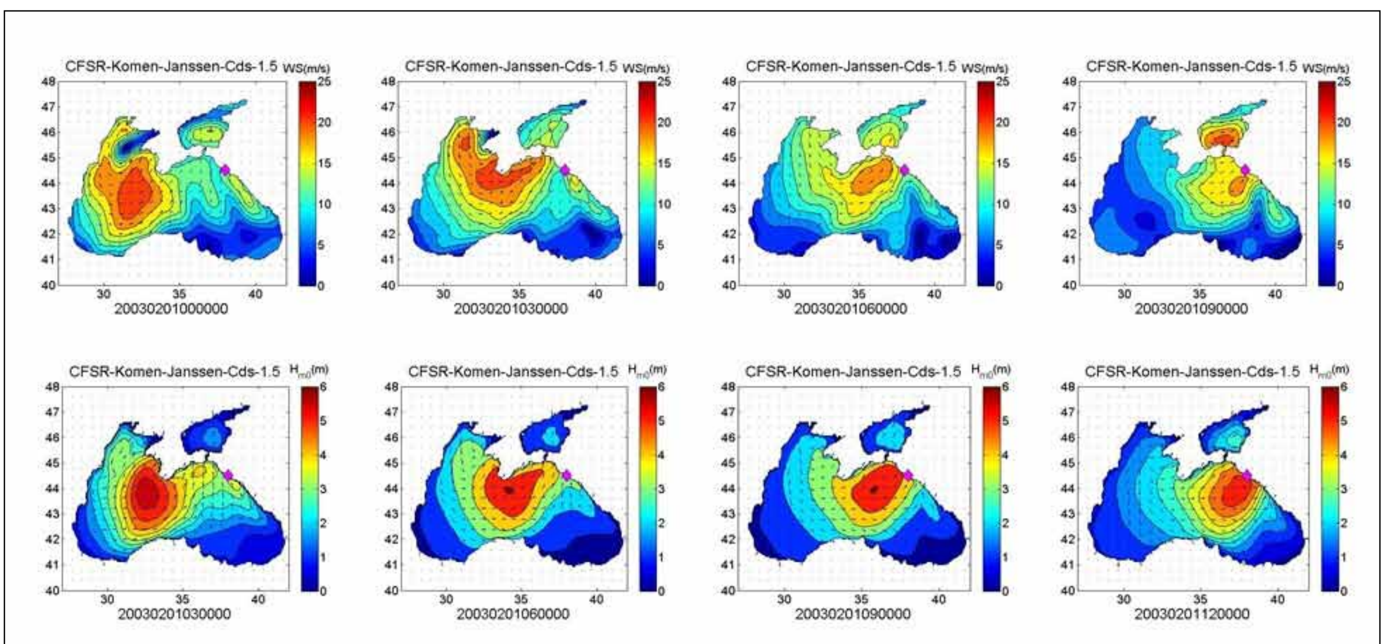

Figure 8. Spatial and temporal development of simulated H_{m0} fields and CFSR wind speed fields and wind and wave direction vectors from the best setting SWAN model simulations forced with the CFSR winds. Pink diamonds in the figures represent the Gelendzhik location.

storm could be tracked. According to the simulated model results, this storm roamed the coastal area of the Turkish city of Sinop (35.0169˚ E, 42.1219˚ N). As per the results, the storm occurred in February 2013.

Based on the present research, it seems there hasn't been much research on the 2013 storm due to lack of buoy data at the location and another factor maybe because it is the most recent storm. The storm appears to have emerged from the northwest Black Sea in the early hours of 23rd of March, 2013, escalated along the southern coast towards the eastern part at Sinop at around 21:00 pm (March 23, 2013) to 12:00 (March 24, 2013) midnight before coming to a halt in the far south eastern part of the Black sea. At its most powerful point, the storm caused wave heights of as high as 5 m along the coast and 7 m at the open sea. The 1-d energy density spectrum from SWAN model shown in Fig. 11, shows that the storm had a maximum value of 438 m^2/Hz at its peak.

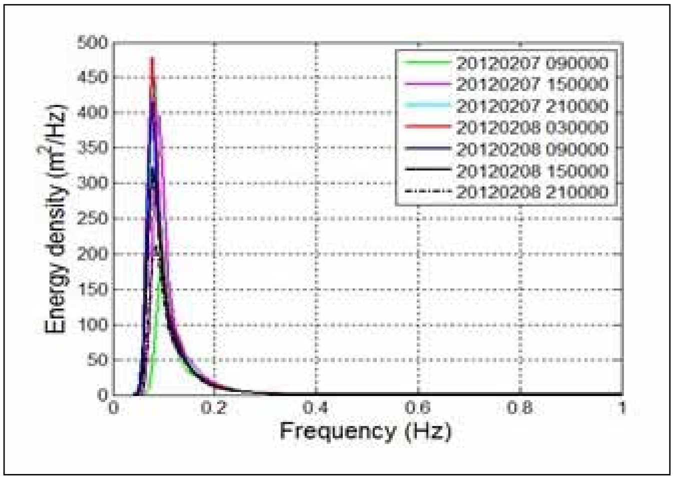

Figure 9. 1-d energy density spectrum simulated from the best SWAN model setting at different hours at Ahtopol.

As the present simulation results, H_{m0} and T_{m02} reached a value of 5 m and 9 s during the peak of the storm at Sinop. Based on spatial and temporal development of simulated H_{m0} and wind speed fields and wind and wave direction vectors from the best setting SWAN model simulations forced with the CFSR winds during the storm the storm could be followed from its origin to end as shown in Fig. 12.

4. Conclusion

The five storms mentioned in this study are modeled using SWAN forced with two different wind inputs of five different combinations, the results of which are later compared with results from previous studies. The comparison results show that the time of storms from measured (available buoy data) data corresponds well with SWAN model's results. Evaluating error statistics and time series comparison, it can be observed that hindcast results of Komen & Janssen combination for wind growth & whitecapping formulations (C_{ds} = 1.5) are quite close to the measurements; therefore it was determined to be the best combination in comparison

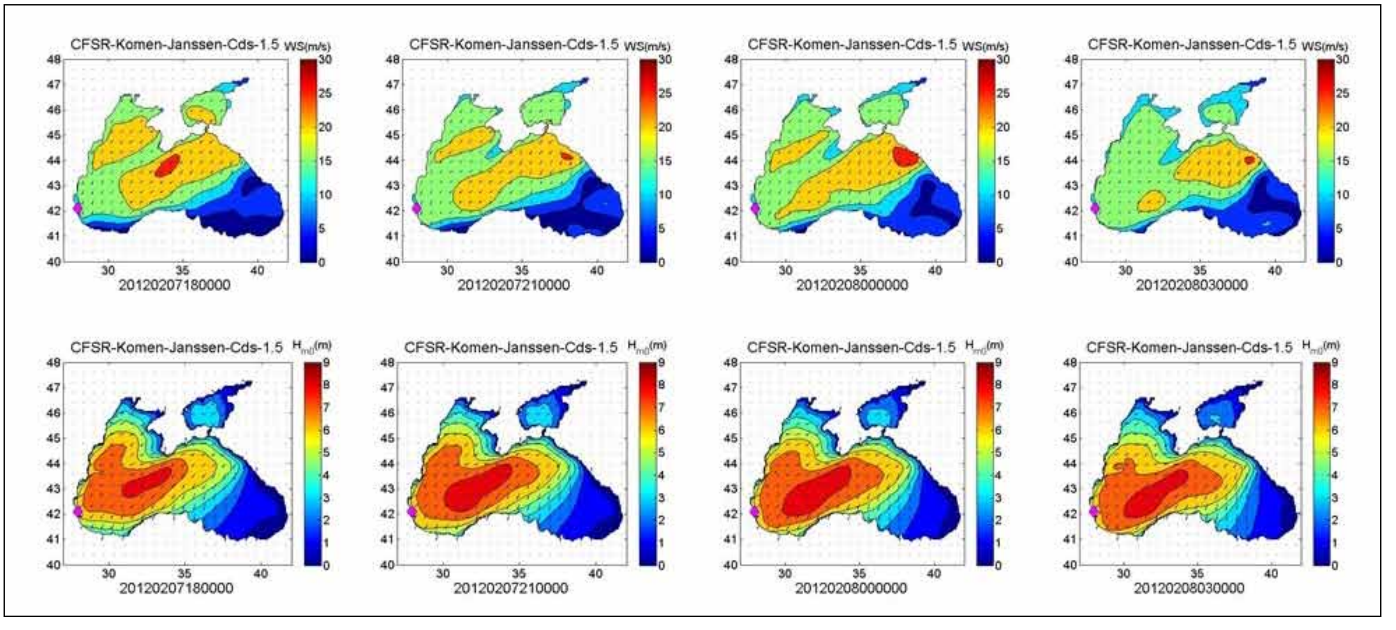

Figure 10. Spatial and temporal development of simulated H_{m0} fields and CFSR wind speed fields and wind and wave direction vectors from the best setting SWAN model simulations forced with the CFSR winds. Pink diamonds in the figures represent the Ahtopol location.

with others. The spatial developments of simulated H_{m0} and wind speed fields and wind and wave direction vectors from the best SWAN model simulations show that the storms were mostly produced by north westerly and north easterly winds. The directions of the wind and wave fields are coherent. It is also observed that wave heights reach the peak at a later time after the wind speeds reach their maximum values.

In the next studies investigation of the return periods of the maximum wave heights and storm surge event are planned.

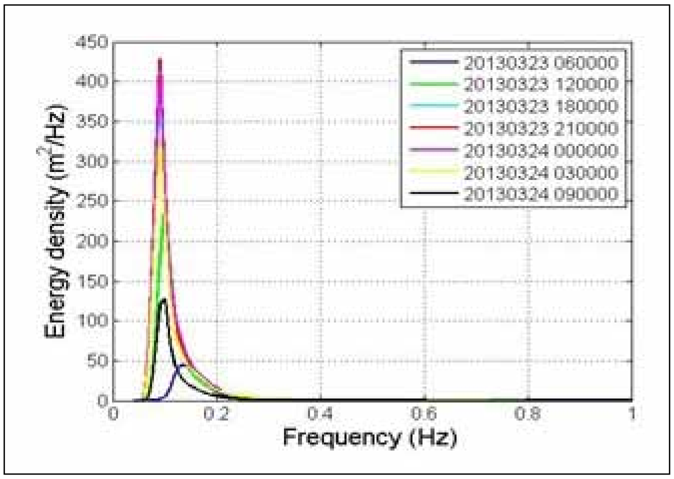

Figure 11. 1-d energy density spectrum simulated from the best SWAN model setting at different hours at Sinop.

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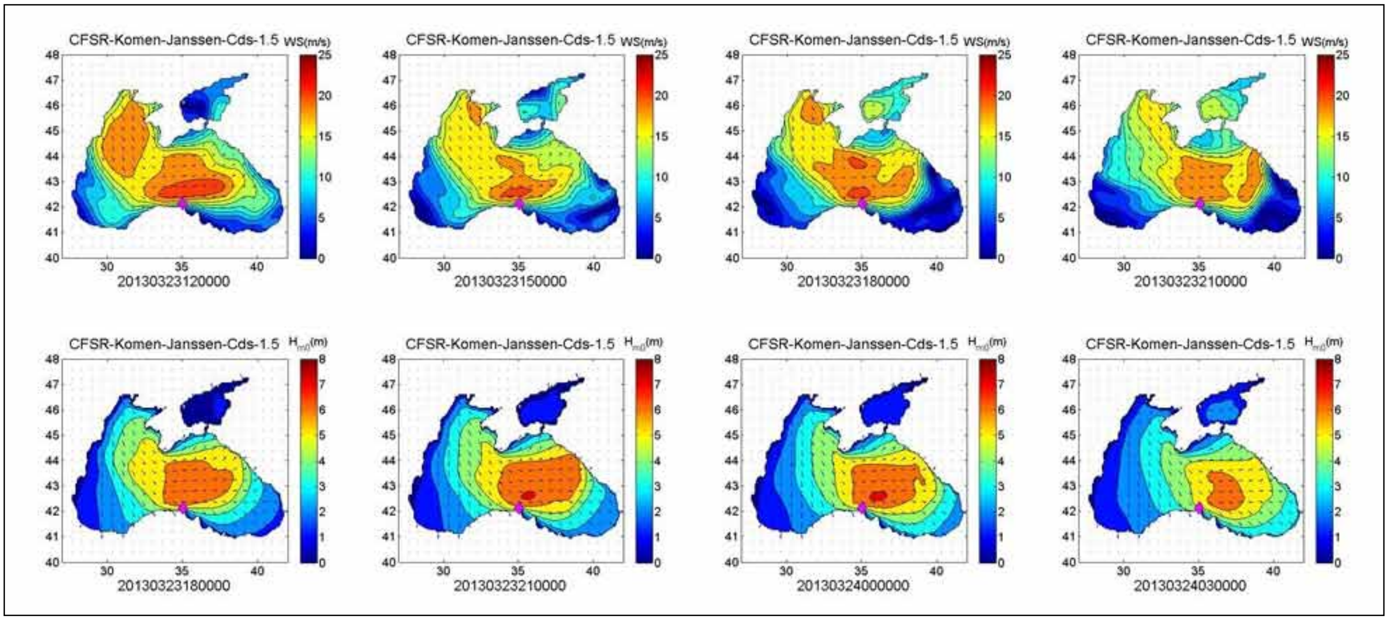

Figure 12. Spatial and temporal development of simulated H_{m0} and CFSR wind speed fields and wind and wave direction vectors from the best setting SWAN model simulations forced with the CFSR winds. Pink diamonds in the figures represent the Sinop location.

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