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The Black Sea waves 2011-2020 - hindcast based on ALADIN wind data

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Abstract: The Black Sea wave climate studies are a hot topic of a scientific research during the last decade. Due to the lack of long enough measurements these studies are based on numerical hindcasts using input wind data from atmospheric reanalysis. The present study follows slightly different approach using input data from an operational regional atmospheric model. We study the wave climate of the Bulgarian coast during the last decade based on numerical hindcast using the SWAN wave model and ALADIN model input wind data. The overall conclusions are that during the period there are no significant changes. The years 2012 and 2015 are notable with higher storminess and 2015 is with the highest wave energy. While in the studies based on reanalysis data the southern Bulgarian coast (represented by Ahtopol) is with a higher values of the storminess indicators, the use of operational model wind data suggests that the northernmost Bulgarian coast (represented by Shabla) is with higher storminess and wave energy than the southern coast.

Keywords: wave climate, Black Sea, wave hindcast, SWAN model

1. INTRODUCTION

Knowledge about the wave climate is important for many practical purposes. Some of the areas, for which the wave climate is important are the preparedness, risk analysis and risk mitigation of coastal hazards such as high waves during the storms, also coastal infrastructure planning, the potential use of the waves as a renewable energy source and others.

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The early studies of the wave climate of the Black Sea were based mainly on the processing of visual observations, based on short periods. The limitation of these studies is the low accuracy of these observations and such studies only provide a qualitative information. Another limitation is the problem of the comparability between different stations (some of which located close to the sea level and others high above the sea level), different quality of the observations between the day hours and night hours, a systematic biases due to different skills of the observers and other problems. Among these studies based on visual observations the study of Polonsky et al (2014) is notable due to the use of semi-instrumental observations (however not at the Western coast) and the finding of low frequency oscillations (with 50-70 years period) and the explanations of the nature of these oscillations given by the authors).

Studies of the wave climate became numerous during the last two decades, and mostly during the last decade due to the application of numerical wave models, availability of atmospheric data for long periods from atmospheric reanalysis, increase in computational power in order to simulate the waves for decadal timespans. The first study of the wave climate of the Bulgarian coast is the study of Valchev et al (2010). The study is based on the use of ERA40 reanalysis and NCEP reanalysis. The limitation of the study is the low spatial resolution of these reanalyzes. The authors further developed their study focusing on the storminess (Valchev et al, 2012). They studied the trends in the storminess proxies. Limitations of the study are again the use of a low spatial resolution input data (NCEP reanalysis) and the focus on a single point for which the storminess data was obtained - the point is close to Emine cape. The approach is sufficient to characterize the overall storminess affecting the Bulgarian coast but it is not possible to reveal the differences between the storm wave climate for the Northern and Southern Bulgarian coast.

Other important studies of the Black Sea wave climate are based on the use of NCEP reanalysis such as (Arkhipkin et al, 2014), on CFSR such as (Akpinar and Bingolbali, 2016; Rusu et al, 2018). The CFSR reanalysis (Saha et al, 2010) is with relatively high spatial and temporal resolution and the referenced studies and many others are based on the CFSR input data. Most of the studies based on CFSR came to a similar conclusion for the Western Black Sea coast - lack of statistically significant trends of the wave climate parameters and storm climate parameters during the last decades and higher storminess and wave heights for the South-Western Black Sea coast compared to the North-Western.

Some of the studies are based not on the general parameters of the wave climate, but on the wave energy (wave power flux) investigating the potential of the waves as a renewable energy source, such as the studies of Rusu (2019) and Tanase et al (2018) among the others. The study with the longest time range (110 years) is the study of the author of the present paper (Galabov, 2015) based on the ERA-Clim reanalysis (Stickler et al, 2014). In this study the conclusion is the last decades of the covered period (until 2010) the wave energy is with a slow negative trend for the Bulgarian coast. ERA-Clim is used also in a study of the Western Black Sea storminess by Galabov end Chervenkov (2018). In this study the authors simulate the Black Sea storms for the period 1900-2010 with a conclusion that there are no statistically significant trends in any of the storm proxies and with a conclusion that some of the most extreme storms affecting the Bulgarian coast are caused by explosive cyclones originating in North Africa and crossing the Mediterranean Sea from South to North instead of the typical West-East movements of the typical Mediterranean cyclones. While most of the studies are based on the use of reanalysis input data, in the present study the author decided to follow a different approach - to use an operational atmospheric model data instead of reanalysis data. As such an approach has never been used, the goal of the paper is not only to investigate the wave parameters at the Bulgarian coast during the last decade, but also to compare the results of the study with the results of the studies based on reanalysis data. The only previous use of operational model data for such a study is the preprint of the author (Galabov, 2015) which contains results based on only 4 years with a focus on the wave energy. The advantage of the use of operational regional atmospheric model input data is not only in the higher spatial resolution of the regional models, but also in the fact, that such regional models are specifically tuned up to work in the area of interest instead of solutions tuned up to work good on global scale. The significant advantage of the approach is therefore, that we expect a more realistic results without some of the biases when using global reanalysis. A limitation of the approach is the short periods of regional model data availability.

2. METHODS AND DATA

The present study is based on the use of the SWAN wave model (Booij et al, 1999). This numerical wave model is a third generation wave model designed especially for the use in coastal regions and suitable for small semi-enclosed seas like the Black Sea. The model simulates the wave energy generation and dissipation taking into account the generation of wave energy by wind, dissipation by whitecapping in deep water and in intermediate in shallow water by bottom friction and depth induced wave breaking. It takes into account also the nonlinear wave - wave interactions in deep and shallow waters. A comprehensive description of the model and details about the configuration of the specific setup of the model used in this study is given in the work of the author (Galabov, 2013) and also in (Galabov, 2015) and (Galabov and Chervenkov, 2018).

The input data for the wave model is coming from the operational limited area model ALADIN - the operational model of NIMH (National Institute of Meteorology and Hydrology) - for more information about the ALADIN model see (Bubnova et al, 2008) and for the Bulgarian implementation (Bogatchev, 2008) and also (Tsenova and Valcheva, 2020). Validation of the winds from ALADIN for the Black Sea shows that they are very accurate especially during the first day of the forecast, which justifies the use of ALADIN data (Galabov et al, 2013). The article also contains data about the accuracy of the implementation of the SWAN wave model in the Black Sea, proving that the model is appropriate for the purposes of the study and with good performance, given the good accuracy of the input wind data . More recent comparison of the winds and the SWAN model performance is available at Dimitrova (2019). Validation of the ALADIN winds We take the model first guess and the forecast for the first 12 hours of each run of ALADIN and then merge them together. By using such approach we assume that the accuracy of ALADIN for the first 12 hours is very high and so we can use such forecast data in order to proceed with the wave hindcast. The spatial resolution of the ALADIN data used in the study is 1/8 degree in spherical coordinates and the temporal resolution is 3 hours. We use the 10m wind components from the ALADIN model to force the wave model. The wave model is running each computation for a period of one year. The start of each year is supposed to be the first of June during the previous year and the end - 31 May of the year. This way the entire stormy season (which is the winter in the Black Sea) is within one yearly period. The spatial resolution of the SWAN output is 1/30 degree in spherical coordinates and the temporal resolution is 1 hour. The wave climate parameters that are evaluated in the study are the mean annual significant wave height (mean SWH), the annual maximum wave height (max SWH), the mean annual wave energy, the number of the storms (above 2.5m max SWH) and the number of significant storms (above 4m max SWH), the annual duration of storms and duration of significant storms. In order to evaluate the storminess we use the storm power index (SPI) which is the duration of a storm in hours multiplied by the squared maximum SWH during the storm. We obtain the sum of the SPI of the individual storms during a single year in order to obtain the annual SPI. The formula that is used to calculate the wave energy (wave power flux) is:

$$E = \frac{\rho g^2}{32\pi} H^2 T_e \approx 0.5 H^2 T_e$$

where ρ is the water density, g is the gravitational constant, H is the significant wave height and T_e is the wave energetic period. E is the wave power flux (called also wave energy) and it is measured in kW/m (kilowatt per meter of the wave front length).

For the purposes of the present study we evaluate the mentioned parameters of the wave climate for two locations - one point close to the town of Ahtopol located at 20m depth in the model bathymetry and another one close to Shabla cape also at 20m depth. These two locations characterize well the wave climate for the southernmost and northernmost Bulgarian coast and highlight the differences between the Northern and the Southern coast. The coordinates of the locations are (λ=27,97°; φ=42,11°) of Ahtopol point and (λ=28,64° ; φ=43,54°) of Shabla point.

3. RESULTS

As it was already mentioned in the previous part, the duration of the period of the numerical wave hindcast is from 01.06.2011 to 31.05.2020 - 9 years. The SWAN wave model has been validated with ALADIN model data starting at 2011 and the results are consistent during the years and therefore we use the period after 2011. Also the ALADIN data is not available with the same spatial resolution before 2011. For the entire period the mean annual significant wave height (mean SWH) is 0,88m for Ahtopol and 0,93m for Shabla. The mean SWH results differ from the mean SWH results based on the use of reanalysis - the use of reanalysis leads to higher value for Ahtopol (and the southern Bulgarian coast in general). The mean wave power flux (also called mean annual wave energy) is 3,70 kW/m for Ahtopol and 3,74 kW/m for Shabla (with slightly higher standard deviation for Ahtopol - 0,66 compared to 0,51 for Shabla). Again the studies based on reanalysis concluded that the South-Western Black Sea coast is more energetic than the North-Western, but the use of operational model data suggests slightly higher energy in the north. This may become an important conclusion, because the shallow northern shelf may be more promising for wave energy extraction even far from the coastline, while at the Southern Bulgarian coast areas with more than 3.5 kW/m will be in too deep water and difficult for exploitation. The patterns of the mean SWH and mean wave energy are shown on figure 1. Generally the shapes of the patterns are consistent with the results of the majority of the studies based on reanalysis input data. The wave energy potential of the Black Sea is below 5 kW/m, which makes the potential of the extraction of wave energy not quite promising, except when using combined wave energy/ wind energy devices. The mean SWH and mean energy are shown for the locations Ahtopol and Shabla on figure 2. There are no evidences of significant trends during the decade and the year with the highest values of both parameters is 2015.

The annual maximum SWH and the storm power index SPI for the two locations are shown on figure 3. The highest SWH are reached during the storm of 07-08.02.2012 (for a detailed study of the storm see the work of Galabov and Chervenkov (2018)). During this storm the SWH reached 6,21 for Ahtopol and 6,47 for Shabla. The higher value for Shabla also comes as a surprise if we compare with the results with different reanalyzes. The mean annual SPI is 4517 for Ahtopol and 4123 for Shabla. The years with the highest SPI are 2012 and 2015.

The storms during 2015 are more than the storms in 2012 but the storms in 2012 are more extreme with the storm of February 2012 being the most extreme - with SPI 2892 for Ahtopol and 2554 for Shabla. These SPI values are much higher than the SPI for all other storms and such values characterize the storm as severe even at oceanic scales. The number of the storms during the years and the number of the significant storms (with SWH above 4m or wave force 6 on WMO scale) are shown on figure 4 and the total annual durations of the storms on figure 5.

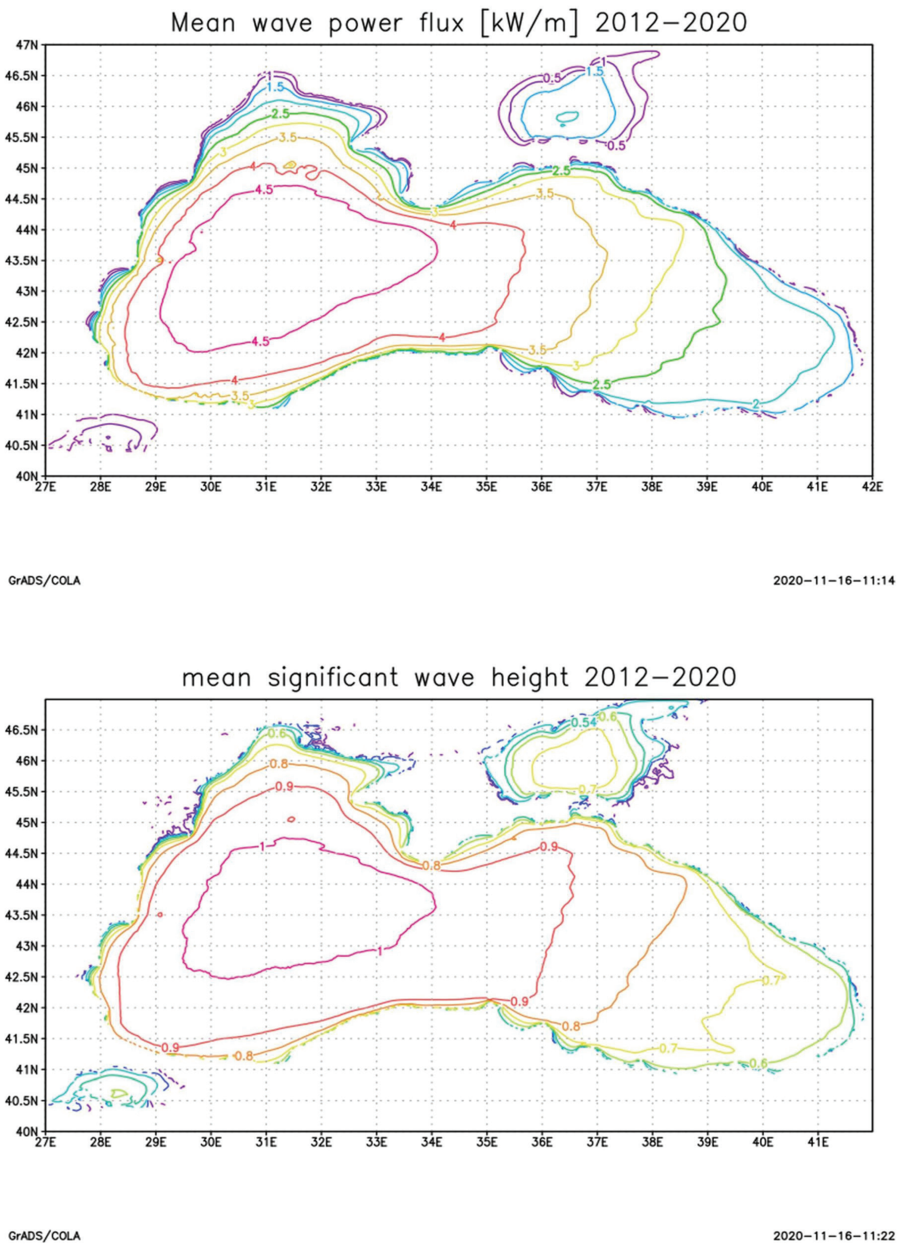

Fig. 1. Mean wave power flux for the Black Sea (upper panel) and Mean significant wave height (lower panel)**.**

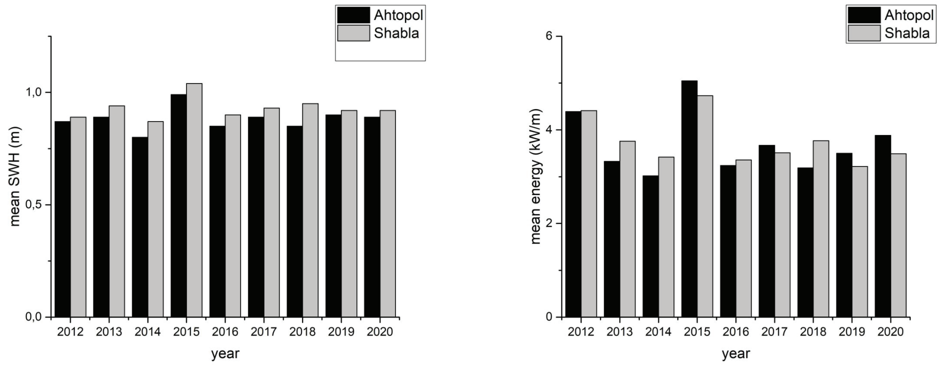

Fig. 2. Mean SWH (left) and mean wave energy (right) for the locations Ahtopol and Shabla

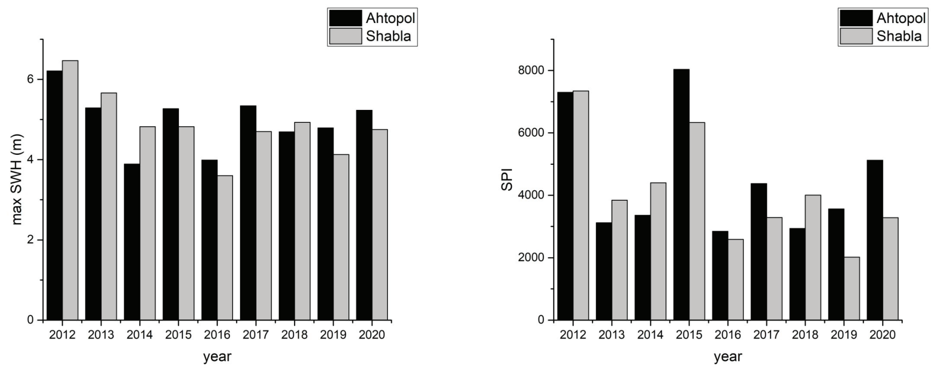

Fig. 3. Annual maximum SWH (left) and the storm power index (SPI) for Ahtopol and Shabla

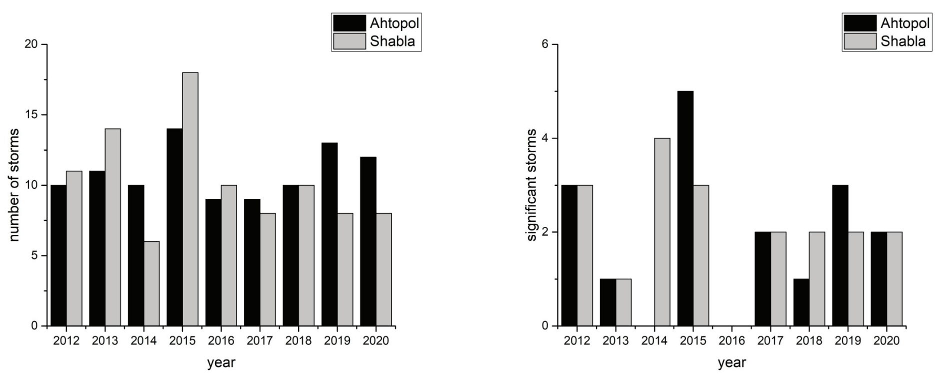

Fig. 4 The annual number of storms with SWH above 2,5m (left) and the number of significant storms i.e. with SWH above 4m for Ahtopol and Shabla

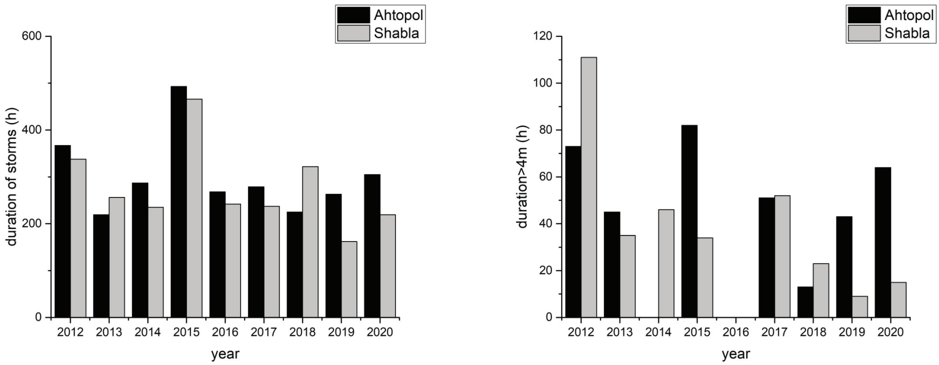

Fig. 5. The total annual duration of storms (left) and total annual duration of the significant storms for Ahtopol and Shabla

We notice that the years 2012 and 2015 are with higher values of these parameters, but 2015 is with much higher values for Ahtopol. The year 2014 is also with high values of the parameters, but only for Shabla and only for the significant events.

4. CONCLUDING REMARKS

In the presented work we studied the wave climate parameters and storminess of the Black Sea focusing on the Bulgarian coast. We used the SWAN wave model with an input data from high resolution operational atmospheric model (ALADIN) instead of atmospheric reanalysis. As far as we know such approach is used for the first time to study the wave climate of the Black Sea. The results generally suggest that the wave climate of the Bulgarian coast is steady, which is in accordance to many studies based on reanalysis input data with two notable years with higher values of the parameters -2012 and 2015. Surprisingly it turns out that the mean annual significant wave height and mean wave energy are higher at the northernmost Bulgarian coast, which conclusion differs strongly from the results when using the reanalysis input data. Taking into account the much higher spatial resolution of the ALADIN model and the fact that the implementation of this model is tuned up specifically for the Black Sea, this finding is important, because it reveals some limitations of the approach based on reanalysis when studying the sub-basin scale spatial differences.

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