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# The Black Sea wave energy: The present state and the Twentieth century changes

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**Abstract:** The article presents a study of the present state of the Black Sea wave energy. The studies of other authors are based on the use of input data from atmospheric reanalysis or a downscaling of such reanalysis. Instead of reanalysis data, we use input data from the operational limited area numerical weather prediction model ALADIN. We show that the highest values of the mean annual wave power flux is between 4.5 and 5.0 kW/m and the near shore areas with the highest wave energy potential are the southernmost Bulgarian coast and the coast of Turkey north of Bosporus. While the reanalysis data underestimates the wave power, it is useful to study the long term changes of the wave power of the Black Sea. We use the 10m winds from the ERA-20C reanalysis, which covers the period 1901-2010 and is an outcome of the ERA-CLIM project. We performed a 110 years hindcast with ERA-20C winds using the SWAN wave model. The results for the area with the highest mean annual wave power shows that there was an increase during the first half of the XX century followed by a small decrease and again a period with elevated wave energy during the seventies. After 1980 there is a decrease of the Western Black Sea wave energy.

**Keywords:** Wave energy, wave power, Black Sea, wave climate, SWAN

## 1. INTRODUCTION

During the last decade there is a growing interest in the field of marine energy as a renewable energy resource. The Black Sea with regards to the energy of the wind waves is considered as a low energy environment, but nevertheless there are studies of the wave energy potential of the Black Sea, because it is important not only in the frame of the renewable energy sources research, but equally important as a parameter of the wave climate.

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The wave energy in the Black Sea as a potential renewable resource was first studied by E. Rusu (Rusu, 2009). In this study the spatial patterns of the wave energy for some typical cases were assessed. Akpinar and Komurcu (Akpinar & Komurcu, 2013) estimated the mean annual wave power flux (hereafter denoted MAWPF) of the Black Sea by numerical hindcast based on input wind data with 6 hour temporal resolution from ERA- Interim (Dee et al, 2011) reanalysis. Their estimation shows that the MAWPF of the Black Sea is below 3 kW/m and the mean annual significant wave height (hereafter denoted SWH) of the Black Sea is below 0.8 m. This value of the mean annual SWH is in agreement with the estimation of Stanev and Kandilarov (Stanev & Kandilarov, 2012) based on numerical simulation using wind data from dynamical downscaling of global reanalysis. Aydogan (Aydogan et al, 2013) used a numerical hindcast based on wind data from ECMWF product (unspecified) also with 6 hour temporal resolution. They estimated that the MAWPF reaches a maximum value above 7 kW/m for the Western Black Sea and values above 6 kW/m for some nearshore locations. Valchev (Valchev et al, 2014) used a dynamical downscaling of a global reanalysis data as an input in their wave hindcast for a longer period of 60 years. Their estimation of the MAWPF is slightly higher than the estimation of Akpinar and Komurcu, up to 3.5 kW/m and they argued that the higher value is due to the inclusion of the period before 1980 which is well known with the higher number and intensity of the storms in the Black Sea (Polonsky et al, 2014; Arkhipkin et al, 2014). Rusu and Onea (Rusu & Onea, 2015) used directly the wave parameters in ERA Interim reanalysis in order to estimate the MAWPF at some locations close to the Western Black Sea coast and their conclusion is that it can reach values above 4 kW/m for the North-Western Black Sea shelf.

This short overview of the studies of the Black Sea wave energy potential shows that there is some discrepancy between the estimates. All previous studies are based on reanalysis data. The reanalysis data has limitations with regards to the estimations of the actual state of the wave energy potential of the Black Sea, for instance the study of Birol Kara (Kara et al, 2005) shows that ERA reanalysis significantly underestimates the Black Sea winds while NCEP reanalysis (Kanamitsu et al, 2002) overestimates the Black Sea winds and is considered by the authors not useful at all for the Black Sea applications due to high discrepancy with the measured winds and too high level of errors. As we argued in our previous work (Galabov, 2013), the way to obtain a reliable estimation of the present state of the Black Sea wave power is to use an alternative source of wind data from a high resolution (both in spatial and temporal meaning) regional atmospheric model that is tuned up especially for the Black Sea. The main aim of this study is to do this by using the operational limited area model ALADIN set up at the National Institute of Meteorology and Hydrology (NIMH) of Bulgaria not only for the routine weather prediction inland but also for the Black Sea. Another aim of the present paper is to study the long term changes in the Black Sea wave power. The recent global reanalysis ERA-20C (Stickler et al, 2014) covers the period 1900-2010 and may be used to perform a long term hindcasts of the wave parameters, taking into account that in ERA-20C only surface data is used and it is more homogeneous in time than the previous reanalyses. It is also available with a temporal resolution of the data of 3 hours which is important for applications such as wave modelling in semi enclosed seas. We present 110 years hindcast of the wave power of the Black Sea and discuss the relation of the changes to the global teleconnection indices in order to identify the reasons for these changes.

## 2. DATA AND METHODS

In the present study we use the SWAN wave model (Booij et al, 1999) version 40.91ABC. Detailed explanation of the model application for the Black Sea is available in (Akpinar & Komurcu, 2013; Rusu, 2009; Arkhipkin et al, 2014). SWAN computational grid regular spherical grid with 1/30$^{o}$ spatial resolution and based on discretisation in spectral space of 36 directions and 31 frequencies between 0.05 and 1 Hz. The model domain covers the entire Black Sea and the number of the computational nodes is 451x211. The interval between the outputs is set to 1 hour.

We compare SWAN simulations of the significant wave heights for a very energetic period from 20 January 2012 to 10 February 2012 using satellite altimetry data from JASON-1 and ENVISAT satellites. The reason for the choice is that it is very important for such kind of studies to ensure that the model performs well not only for average but also for high energy conditions.

We test four different combinations of parameterizations of the wave energy generation by wind and dissipation due to whitecapping - the WAM cycle IV parameterization scheme (wind input based on the theory of Janssen (Janssen, 1991) and pulse based whitecapping (Hasselmann, 1974), the WAM cycle III parameterization scheme (wind input formulation of Komen (Komen et al, 1984) and pulse based whitecapping) with two values of the tuning parameter $\delta$ in the whitecapping parameterization: $\delta=1$ (known as “Rogers trick” (Rogers at al, 2003) ) and $\delta=0$ (default in the previous versions of SWAN) and also the parameterizations of Westhuysen (Van der Westhuysen, 2007) based on saturation based whitecapping and alternative version of the generation by wind.

The wind input data for the wave model is from ERA-20C reanalysis for 110 years and also ERA-Interim for reference and NCEP reanalysis II. To estimate the present state of the Black Sea wave power we use the operational limited area atmospheric model ALADIN (Bubnova et al, 1995; Tsenova and Valcheva, 2020) used routinely to drive the Bulgarian operational wave forecast and storm surge forecast system. We take the initial model output +0 hours and also the model forecast for +3 hours, +6 hours and +9 hours and then we continue with the initial output of the next model run (the model starts twice daily) and the next 9 hours forecast. The horizontal resolution of the wind data from ALADIN is 0.125$^{o}$. The hindcast with ALADIN data covers the period from

01.06.2011 to 31.05.2015 because the ALADIN wind data is not available with the same spatial resolution for the previous years for the Black Sea domain.

The wave power flux is estimated by the formula:

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e \approx 0.49 H_s^2 T_e \qquad (1)$$

where $H_s$ is the SWH, $T_e$ is the wave energy period (minus first momentum divided by zero momentum of the wave spectrum) and ρ is the surface water density taken as constant.

In our simulations the year does not start at the beginning of January, but in low energy month – we selected first of June as the beginning of the year to ensure that the entire high energy winter season is within one year and not artificially separated and so for instance year 2012 means the period 01.06.2011 to 31.05.2012.

## 3. COMPARISONS WITH SATELLITE DATA

We compared with satellite altimetry data the simulations by SWAN of the SWH for the specified in the previous section wind sources and parameterizations for a period of 20 days with very high wave energy for the Black Sea. The results are summarized in Table 1.

**Table 1.** Comparison of SWAN model runs with different input winds and different source terms parameterisations with satellite altimetry measurements of SWH from Jason 1 and Envisat satellites. The period is from 20.01.2012 to 10.02.2012. RMSE denotes root mean square error, R- correlation coefficient and SI the scatter index.

| **Wind data source** | **source terms parameterization** | **SWH observation mean** | **SWH model mean** | **Bias** | **RMSE** | **R** | **SI** |
|---|---|---|---|---|---|---|---|
| ALADIN | Westhuysen | 2.93 | 2.55 | -0.38 | 0.68 | 0.80 | 0.23 |
| | Janssen | | 2.57 | -0.36 | 0.63 | 0.81 | 0.21 |
| | Komen | | 2.53 | -0.41 | 0.69 | 0.78 | 0.23 |
| | Komen, δ=1 | | 2.77 | -0.16 | 0.59 | 0.90 | 0.20 |
| ECMWF analysis | Komen, δ=1 | | 2.50 | -0.43 | 0.70 | 0.75 | 0.24 |
| ERA-Interim | Komen, δ=1 | | 2.25 | -0.68 | 0.90 | 0.55 | 0.31 |
| NCEP Reanalysis II | Komen, δ=1 | | 3.37 | +0.44 | 1.27 | 0.75 | 0.43 |

The bias of the SWH when using the ALADIN wind input data is lowest with the Komen option with δ=1 (and also the RMSE and scatter index are the lowest) and highest underestimation is when using Komen with δ=0. Because the estimation of the wave power flux depends on the square of SWH, high biases are undesirable, they can easily lead to erroneous results due to multiplication of errors. Therefore we chose Komen,

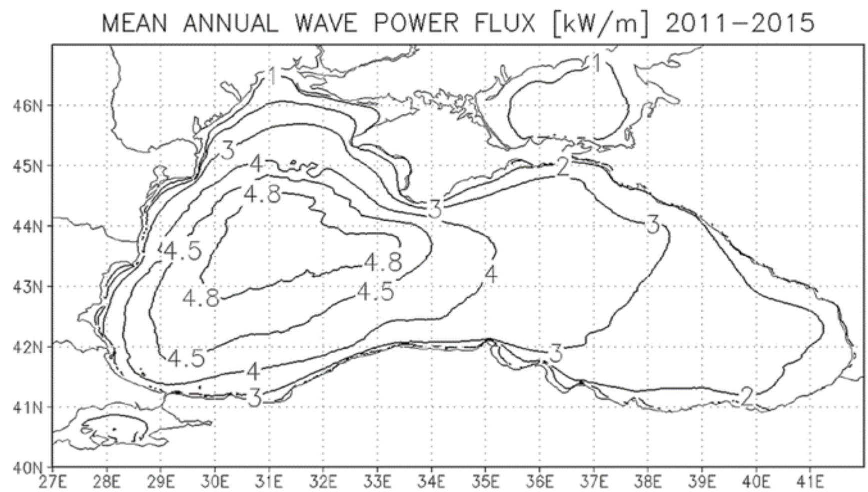
$\delta$=1 in our hindcasts. The simulations based on ECWMF operational analysis and ERA-Interim lead to too high negative biases of SWH (which explains the low wave power of the Black Sea estimated by Akpinar and Komurcu). The NCEP Reanalysis II leads to high overestimation and high scattering, making it inapplicable for such studies in the Black Sea. The usage of ALADIN wind data outperforms the studied reanalyses for the SWH and is preferable for wave power estimations also for its high resolution.

**Table 2.** Mean annual wave power flux for some selected points for the period 2012-2015.

| Name of the point | Latitude,° | Longitude, ° | Description of the location | Mean annual wave power flux, kW/m |
|---|---|---|---|---|
| Ahtopol | 42.20 | 28.20 | Near Ahtopol- southernmost Bulgarian coast | 4.00 |
| Shabla | 43.60 | 28.90 | Near cape Shabla- close to the border Bulgaria- Romania | 4.01 |
| North Western Shelf | 44.81 | 30.00 | In the North Western Shelf close to Danube delta | 3.88 |
| Crimea | 42.27 | 33.70 | South of Crimea Peninsula | 3.48 |
| Gelendzhik | 44.50 | 37.98 | Close to Gelendzhik, Russia- north-eastern Black Sea | 2.20 |
| Sinop | 42.19 | 35.0 | Close to Sinop- Turkey- central southern coast | 3.73 |
| Batumi | 41.65 | 41.35 | Close to Batumi- south-eastern coast | 1.79 |
| Bosporus | 41.50 | 29.0 | North of Bosporus-south western coast | 4.22 |

## 4. ESTIMATION OF THE PRESENT STATE OF THE BLACK SEA WAVE POWER

The estimation of the Black Sea wave power and the mean annual SWH for the period 01.06.2011 - 31.05.2015 when using ALADIN wind input is presented on Figure 1 MAWPF reaches values of 4.8 kW/m for the recent four years and mean annual SWH is slightly above 1m. The areas with the highest wave power (in agreement with the other studies) are the Turkish coast north of Bosporus and the southern Bulgarian coast but also in some areas in the north-western shelf. This is above the estimations based on reanalysis but below the values obtained by Aydogan (Aydogan et al, 2013). A possible reason is that in their study the presented validation of their model shows that they are working with positive biases for the SWH and wave period for the most energetic measurements location presented and two positive biases easily lead to significant overestimations. In Table 2 we present the estimation of the MAWPF for 8 selected locations. All locations are with depth in the model bathymetry between 50 and 100 m (so all of them are in deep water with regards to wave modelling) and 10 to 30 km from the coastline. As it can be seen, the wave power is above 4 kW/m for the Western Black Sea shelf and lowest for the south eastern Black Sea. Figure 2 shows the variations of the mean monthly wave power flux for the location Ahtopol. The winter months are with mean wave power reaching for some months values above 10 kW/m, while the summer months are with low wave power. The highest value is for February 2012 but the year with the highest mean annual value is 2015 (01.06.2014-31.05.2015) with MAWPF for Ahtopol above 5 kW/m. When ERA-Interim winds are used, the wave power is significantly underestimated for the months with the highest energy. The estimation shows that the waves with SWH above 1m have a contribution to the MAWPF of 87% of its value and the waves above 2 m - 56% share of MAWPF, but their frequency is low. The waves are above 1m  only 29% of the total time of the hindcast and these above 2 m - just 7% of the time. The value of the MAWPF is mainly due to contribution of short lasting high energy episodes and very low energy otherwise. With regards to the directionality of the wave power, for Ahtopol the energy comes mainly from northeast with relatively low directional spreading, but generally there are no significant differences with the other authors about the directions of the wave energy transfer.

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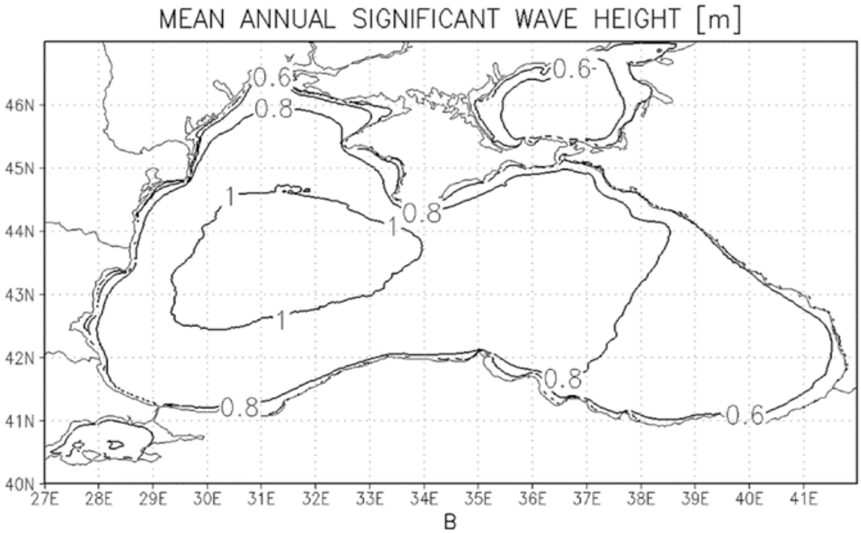


**Fig. 1.** SWAN hindcast with input wind data from ALADIN atmospheric limited area model for the period from June 2011 to May 2015: A) mean annual wave power flux (MAWP); B) mean annual significant wave height.

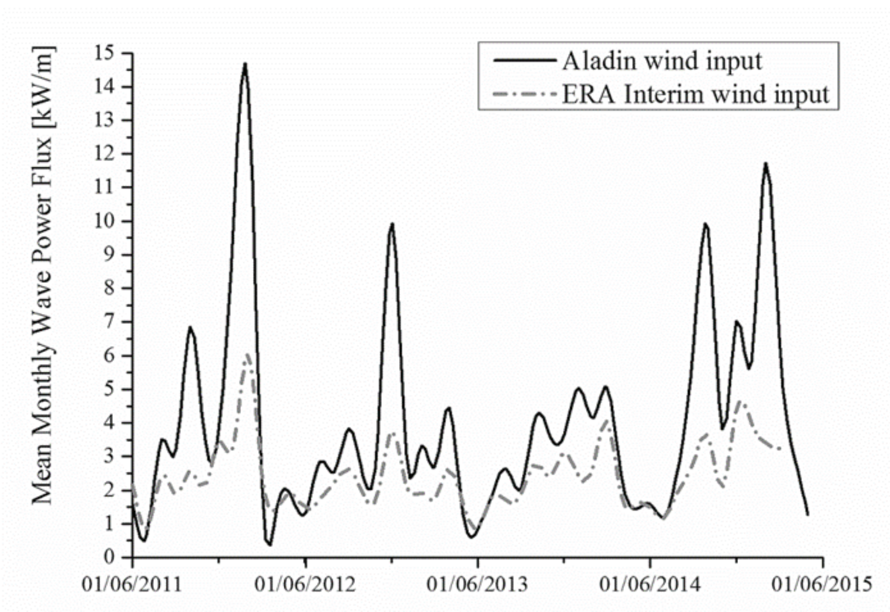


**Fig. 2.** Variation of the mean annual wave power flux during the period 06.2011-05.2015 at Ahtopol location based on ALADIN and ERA-Interim wind input data.

## 5. CHANGES OF THE BLACK SEA WAVE ENERGY FOR THE PERIOD 1900-2010

To evaluate the wave energy's changes during the last 110 years, we performed a simulation with SWAN using ERA-20C wind input. The comparison of simulations with ERA-20C and ERA-Interim winds for the period 1979-2010 shows that the results with the two reanalyses are consistent with slightly higher values when using ERA-20C due to the higher temporal resolution of the data. In the Table 1 we presented comparison with measurements for the entire Black Sea, and we have to mention, that the statistics for the Western Black Sea are significantly better for both ALADIN and ERA-Interim (and so the same is expected for ERA-20C) while for the Eastern Black Sea they are significantly poor. Due to that reason we consider that the conclusions from the long hindcast are reliable only for the western part.

Figure 3 shows the changes of the wave power for Ahtopol and Shabla locations. A smoothed curve of the changes was obtained by use of low pass Fast Fourier Filter (FFT) with cut-off frequency of 0.05. The form of the curve is qualitatively the same when using moving average with 10 years period of averaging. For both locations there is an increase during the first 50 years of the XX century (the positive trend is statistically significant at level of significance 0.01 using Mann-Kendal test). After that there is a decrease with some increase during the seventies and negative trend after that (also statistically significant at level 0.01 by Mann-Kendal test). The changes are mainly due to the changes of the wave regime of the waves below 4 m SWH that follow such trend and are with the greatest contribution to MAWPF, while for the waves above 4 m SWH (stormy conditions) the behaviour is different - there are no signs of trends, but rather of a low frequency oscillations such as those found by Polonsky (Polonsky et al, 2014) for the storms in the Northern Black Sea with a period of 50-60 years. For Crimea there is a steady increase of the wave energy for the entire period until the end of seventies and decrease after that. Even if we argued that the results for the eastern part of the sea are not so reliable, we should mention that the seventies are particularly interesting, because there is a high value of the wave energy for the entire Black Sea. The maximum decadal mean wave power of the Black Sea (the highest value in the entire sea) for the 110 years period increased from 2.7 kW/m (remember that due to the underestimation the absolute values are not important but only the dynamics) to 3.3 kW/m during the decade 1941-1950. Then it decreased to 3 kW/m in the period 1951-1970 and raised again to 3.3 kW/m during the seventies and after that decreased to 2.7 in the last decade (see Figure 4).

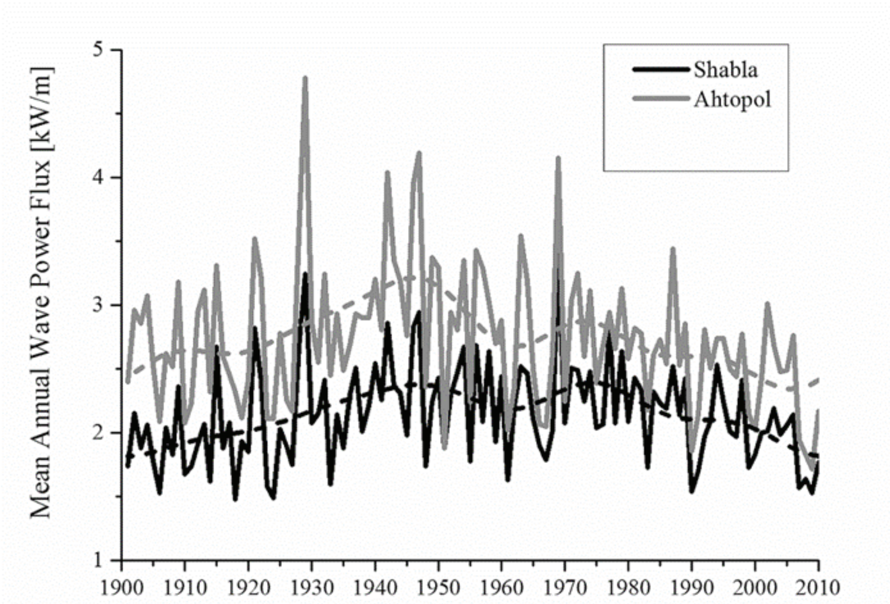


**Fig. 3.** 110 years hindcast (based on ERA-20C winds) of the mean annual wave power flux at Ahtopol and Shabla locations- annual data and smoothed by low pass FFT filter with 0.05 cut off frequency.

## 6. LINKS OF THE CHANGES TO THE GLOBAL TELECONNECTIONS

We studied the correlations of the mean monthly and annual wave power to the global teleconnections such as North Atlantic Oscilation (NAO), East Atlantic/West Russia (EA/WR) pattern, Southern Oscilation Index (SOI), Arctic Oscilation, Scandinavia index, Mediterranean Oscilation Index (MOI) and others and also the patterns of the ocean surface temperature- Atlantic Multidecadal Oscilation (AMO) and Pacific Decadal Oscilation (PDO). For the Northern Black Sea Polonsky found that the main factor driving the low frequency oscillations of the storminess is the interplay of AMO and PDO. Our study confirmed this finding also for the wave power. Multivariate regression shows that the correlations of the wave power for Crimea with AMO and PDO are significant and the combined AMO+PDO oscillation correlates with the wave power changes there with correlation coefficient R=0.61 and the wave power there is highest when both AMO and PDO are in negative phase. For the Western Black Sea wave power this is not the case. The correlation with AMO and PDO is not significant and is below 0.1 and obviously the processes that determine the wave power changes and so the average wave climate (not the storminess climate that needs further studies) is affected by different reasons. Only the correlation with NAO and EA/WR was found to be significant at p-value of 0.05 using Pearson test and there is a higher correlation with EA/WR (but only for the period after 1950 for which there is a data for EA/WR) than the correlation with NAO. For Ahtopol the correlation with EA/WR is 0.35 (significant at level of significance 0.01 by Pearson test) and with NAO is -0.27 (negative NAO phase leads to higher wave energy). So for the Western Black Sea the wave power depends not only on the NAO (defined as a meridional difference) but also on the zonaly defined EA/WR. The multivariate regression analysis shows that the multiple correlation with the teleconnections is 0.49 and obviously significant part of the variations remains unexplained. For the north western shelf (Shabla location) there is a higher correlation with NAO -0.33 and 0.25 with EA/WR.

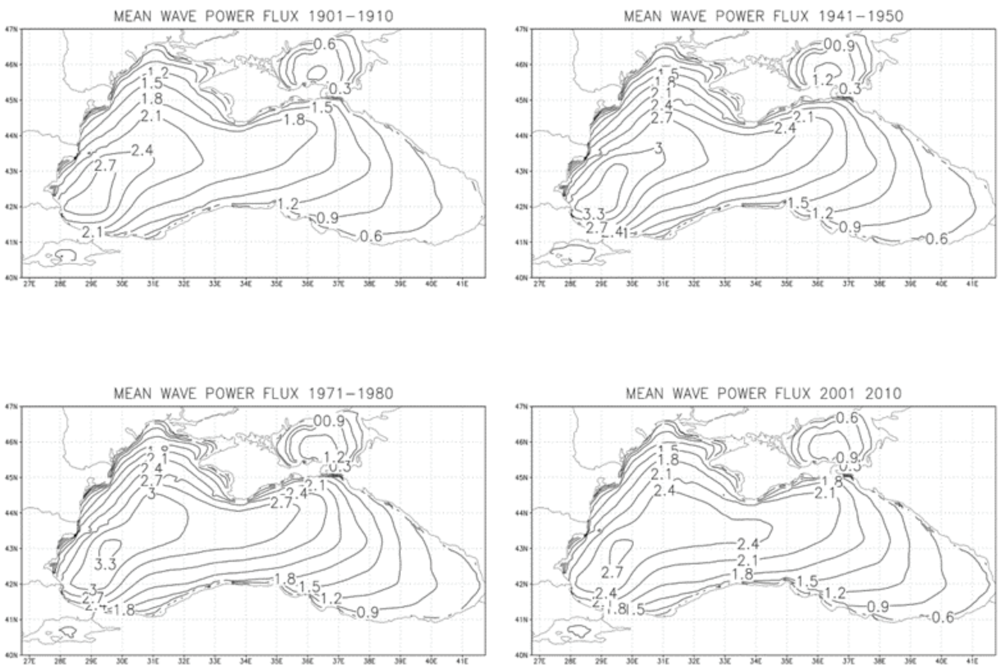


**Fig. 4** Mean decadal wave power flux changes - upper left: 1901-1910; upper right: 1941-1950; lower left: 1971-1980; lower right: 2001-2010

In general the correlation with NAO decreases from north to the south at the Western Black Sea. The positive correlation of the wave power for the western coast with EA/WR may be explained by the observations that when the winter EA/WR is positive, there is more frequent meridional transport of cold air over the Eastern Mediterranean region and more frequent episodes with strong winds (Nissen et al, 2010) and may also influence the phenomena of blocking of the Mediterranean cyclones, that is known to cause the most significant storms affecting the Western Black Sea coasts and leading to periods with high wave energy. Surkova et al. (2013) used a future climate projection of the Black Sea storminess and concluded that the storminess of the Black Sea is expected to decrease and we may speculate that this also means a further decrease of the Western Black Sea wave energy as well, but if the wave power of the Western Black Sea is affected by NAO and EA/WR, then it should be mentioned that it is still unknown how these patterns are affected by the anthropogenic contribution to the global warming.

## 3. CONCLUDING REMARKS

The present state of the Black Sea wave power was estimated based on the period 2012-2015, using wind data from the limited area atmospheric model ALADIN. It was found that the mean annual wave energy flux reaches 4.8 kW/m for the South Western Black Sea and above 4 kW/m for the western shelf. A 110 years wave hindcast was performed to evaluate the changes in the wave power and it was found that the wave power increased during the first half of the XX century for the western part of the sea (where it is highest) and decreased after the seventies. The study of the influence of the teleconnections showed that the changes in the wave power at the western shelf are driven by other factors (mainly linked with NAO and EA/WR) than the northern and eastern part of the sea, where it is linked with AMO and PDO and highest when they are both negative.

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