Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 7, Issue 3 / 2022, pp. 349-362
http://doi.org/10.56958/jesi.2022.7.3.349

D. Environmental Engineering and Energy

Received ***27 Apryl 2022*** *Accepted* ***14 September 2022***
Received in revised form ***9 June 2022***

A MATLAB toolbox for analysis of the environmental matrix in open seas and coastal areas

LILIANA RUSU*

Faculty of Engineering, "Dunarea de Jos" University of Galați
47 Domneasca St., Galati, Romania

Abstract: Given the climate changes that are becoming more evident in recent years, the assessment of their impact on the dynamics of the environment matrix over extended periods is needed. In this paper, the results obtained using a Matlab toolbox developed to provide numerical and graphical outputs for a quick assessment of the present and future wave and wind climate are presented. Based on the wave and wind simulation data, quick information about the sea states or wind conditions over an area or in selected points are provided as output. These include annual, seasonal and monthly statistics, trends, bivariate distribution of the wave parameters, wind speed magnitude, average wave and wind energy, analyses of the extreme events, etc., Such results are of interest for various applications in the marine environment.

Keywords: environmental analysis, Matlab toolbox, marine environment, climate change.

1. Introduction

Nowadays, the effects of climate change on the weather are becoming more evident, being felt mainly due to the more frequent presence of extreme events, but not only [1]. The climate change topic and stopping its evolution is in the attention of most countries. A step forward made by the European Union (EU) is the adoption of long-term strategies aiming for the transformation of the European continent into the first world climate-neutral territory by 2050. These measures are included in the European Green Deal [2], a broader plan adopted with the scope to reduce greenhouse gas emissions by at least 55% by 2030, compared to the 1990 levels.

Marine environment is strongly affected by climate change and the assessment of the effect on sea state conditions is of major importance due to their influence on

*Correspondence address: Liliana.Rusu@ugal.ro

maritime transportation, as well as on other activities that occur in the nearshore or offshore areas. In addition, in the recent years, a strong emphasis on finding renewable sources for the production of clean energy has been noticed [3], and the marine environment presents various opportunities for exploiting renewable energy resources (e.g. from wind, waves, and currents) with great potential to ensure a significant part of the future energy demands [4].

The sea state conditions respond to global climate variability and change and the assessment of the changes in the wave climate represents an important issue that has received increasing attention in the last years. Thus, the Intergovernmental Panel for Climate Change (IPCC) in the Fifth Assessment Report (AR5) brought attention to the scientific community regarding the low confidence of the wave projections in some regions due to the limited number of model simulations [5]. Following these directions, the scientific community around the world along with various international modelling groups have intensified their efforts in producing several wave projections (usually until the end of the century) at a global scale using various atmospheric fields to force numerical wave models [6, 7, 8].

However, the simulations at a global scale cannot represent accurately the specific particularities of each region, especially regarding the extreme weather events. These information gaps can be completed using the regional simulations when the wind fields from the Regional Climate Models (RCMs) are used as input for the wave model. The wave models driven by RCM higher resolution wind fields allow solving physical processes into smaller scales and consequently with increased detail and realism than the global models [9].

Generally, to assess the wave climate in a certain area (extended areas such as oceans or seas, or a local coastal area), information that covers an extended period of data is needed. Slices of thirty years of data are considered by the World Meteorological Organization (WMO) long enough to calculate an average that is not influenced by year-to-year variability [10]. Given the large amount of data to be processed and analysed to conduct climatological studies regarding the evolution of the marine environmental matrix (wave and wind) in the recent past and its dynamics in the future, these require the use of tools with computing capabilities to provide numerical output and also quick and comprehensive graphical output.

In this paper, results obtained using the initial tools developed by the author using the Matlab environment to provide numerical and graphical outputs for a quick assessment of the present and future wave and wind climate are presented. Case studies with applications in the Black Sea are here illustrated, but this toolbox is now being integrated into an original computational platform denoted as 'WAve Climate Assessment – WACA' that will be developed in the framework of the CLIMEWAR project (CLimate change IMpact Evaluation on future WAve conditions at Regional scale for the Black and Mediterranean seas marine system). However, the capabilities of this interface can easily be extended to any marine or coastal area of the globe.

2. Methods and materials

A diagrammatic scheme describing the toolbox capabilities is presented in Figure 1. First of all, RCM wind speeds at 10 m over the sea level (U10) provided as zonal and meridional components of the wind velocity by various databases are pre-processed to extract the data covering the target area and also to generate the wind fields in the format required by the wave model. These wind fields are then used to force the wave model implemented in the computational domain covering the area of interest, in this case, the SWAN (Simulating WAves Nearshore, [11]) model implemented in the Black Sea basin [12].

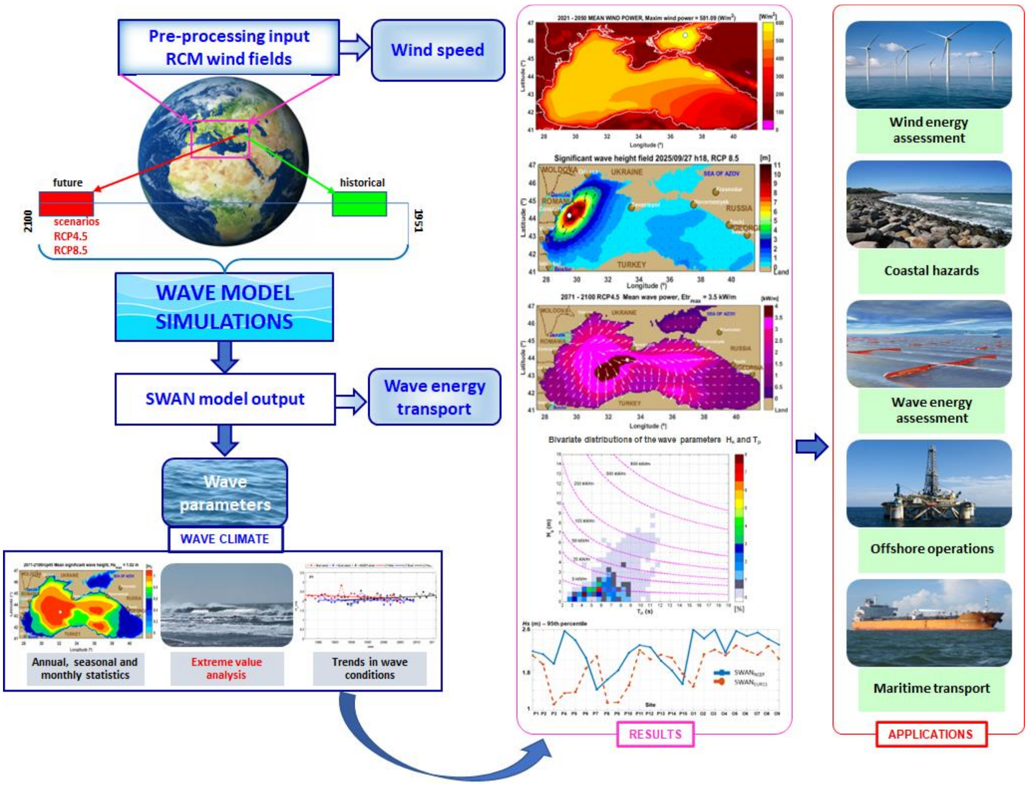

Fig.1. Flowchart of the capabilities provided by the toolbox.

In addition, these wind fields can also be useful for various purposes, such as assessing the wind power potential in offshore areas [13]. The exploitation of offshore wind energy has seen strongly developed recently, especially because in these areas the wind power potential is higher than on land, and in this way, the efficiency of the wind farm is greater.
The use of highly accurate wind fields to drive the wave model is of utmost importance in obtaining reliable simulation results. Additionally, the adequate model parametrization for the sea state conditions existing in the target area, tested

and decided in its calibration process, also represents a key factor to obtain accurate information about the waves. Moreover, validation of the model results against in-situ or altimeter measurements increases the confidence in the data provided by the model.

The SWAN model has as output data, besides the main wave parameters, many other variables with applicability in various fields of the marine environment, such as wave energy exploitation, coastal protection, the evolution of sediment transport and beach morphodynamics induced by waves, and so on. The next section presents the capabilities of the interface in providing useful and comprehensible information for various users, regarding the recent present and future wave and wind climate.

3. Results

Based on wave and wind simulation data, quick information about the sea state or wind conditions (annual, seasonal and monthly statistics, trends, bivariate distribution of the wave parameters, wind speed magnitude), average wave and wind energy, analyses of the extreme events, etc., over an area or in selected points are provided as output.

3.1 Spatial analysis

Based on the results obtained with the SWAN model in each point of the computational domain, with a time step of 3 hours for the period in which the simulations were performed, the wave and wind spatial distribution for a certain time frame can be easily visualised with help of the Matlab toolbox presented here, as it is illustrated in Figure 2. In both panels of Figure 2, the absolute values of the parameters are represented in the background, while in the foreground the wave and wind vectors, respectively. This allows the users to analyse the sea states and wind conditions that existed at a certain time when a maritime event occurred (such as naval accidents) and to study if its occurrence was influenced by weather conditions [14].

The averages of the simulated wave parameters can also be computed for any period within the maximum simulation interval, with the spatial visualisation of values obtained. An example is illustrated in Figure 3 where the spatial distribution of the future average significant wave height (*Hs*) field obtained under RCP4.5 (Representative Concentration Pathway) scenario and the corresponding mean wind speed field are presented for the period 2071-2080. In order to highlight the seasonal or monthly variability of the average values of the studied wave parameters, it is necessary to group the results by seasons or months for a certain time interval and all these calculations can be performed with this toolbox.

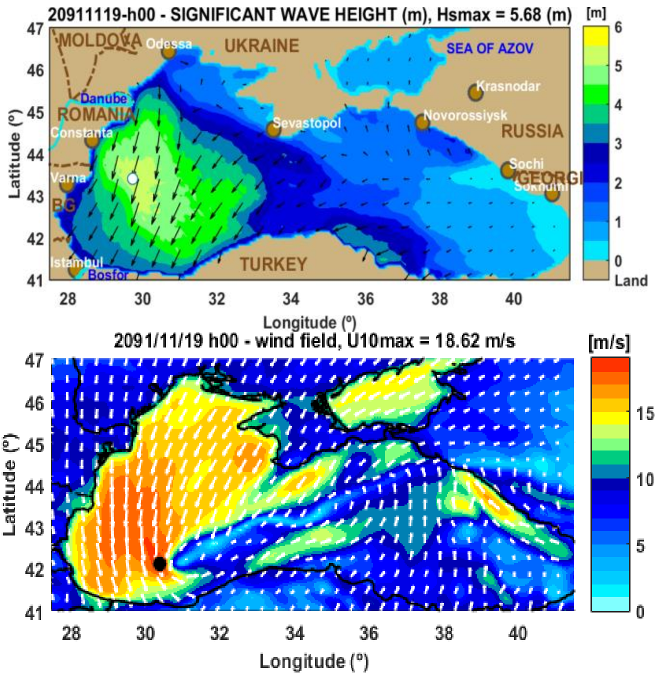

Fig. 2. Visualisation of the spatial distribution of *Hs* field simulated by SWAN model (top panel) and U10 field (bottom panel) for the time frame 2091/11/19 h00.

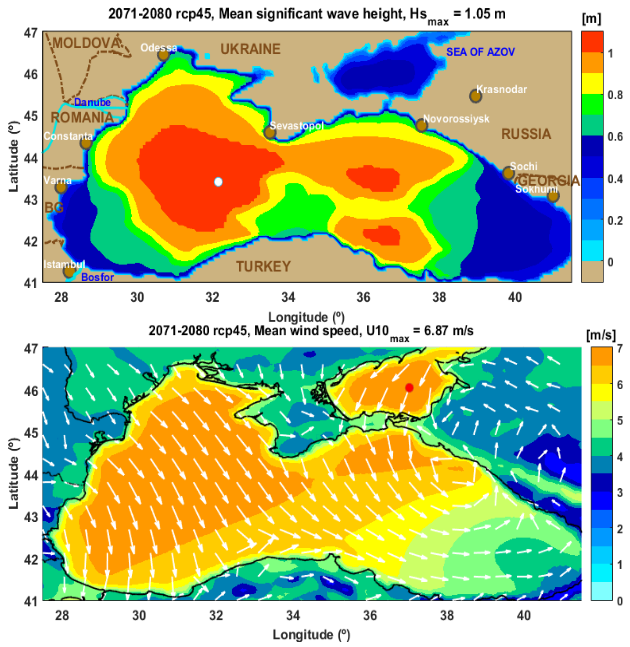

Fig. 3. Spatial distribution of the average *Hs* field resulted from the SWAN simulations (top panel) and the mean wind speed field (bottom panel), for a 10-year time interval (2071-2080).

The data obtained from the climate models are affected by several sources of disturbance and the combined effect of these causes leads to a bias between observations (that are present in the reanalysis) and the simulated climate events. This bias needs to be quantified for further corrections and it is computed as the difference between the historical and reanalysis data, as illustrated in Figure 4.

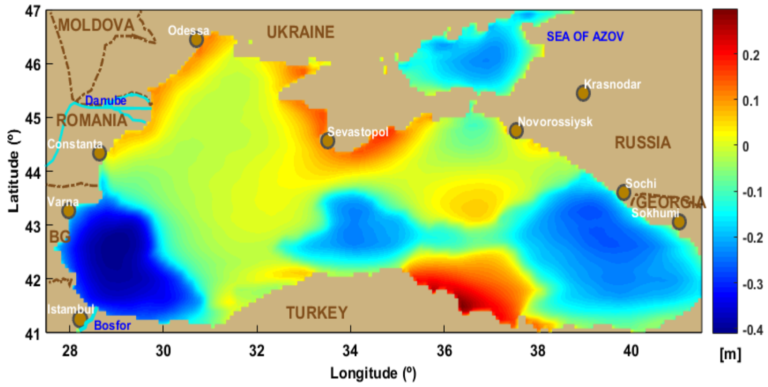

Fig. 4. The *Hs* bias between historical and reanalysis results for the recent past period 1987-2005.

The dynamics of the mean wave parameters over a future period, in comparison with the historical mean values, are analysed using the mean relative change (*MRC*) computed as the difference between the mean values corresponding to future and historical means, divided by the historical means, i.e.,

$$\overline{MRC} = \frac{\overline{MF}-\overline{MH}}{\overline{MH}} \times 100 \qquad (1)$$

where $\overline{MF}$ is the mean wave parameter over the future period, while $\overline{MH}$ represents the mean wave parameter over the historical period. The outputs are given as a percentage relative to the historical period (usually considered 1975 – 2005), as illustrated in Figure 5.

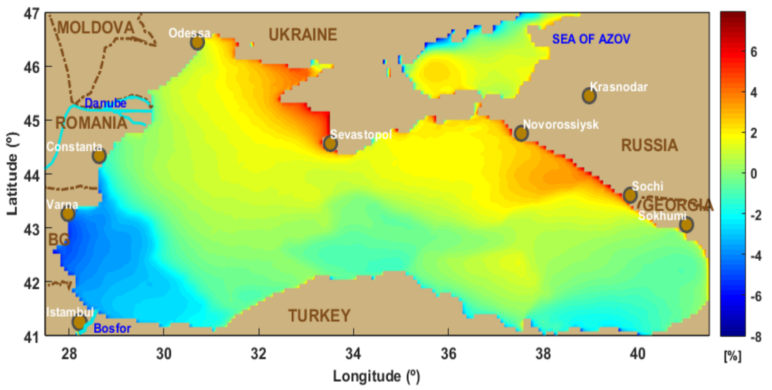

Fig. 5. Changes in terms of mean *Hs* as a percentage relative to the historical period for the future period 2071-2080, corresponding to the RCP4.5 scenario.

As mentioned earlier, the production of energy from renewable sources is an important goal of the European Union, and the energy of wind and waves is in the spotlight. Such investments for the development of the wind and/or wave farms require a preliminary assessment of the resources to find the best locations for efficient harvesting. This assessment can be done based on extended measurements, but it is difficult to cover all possible locations of interest. Therefore, the use of the results of simulations with numerical models covering large areas has become very attractive, especially since their accuracy has greatly increased in recent years.

Thus, in the nodes of the computational grid of SWAN model the wave transport components (i.e. energy flux per unit of the wave crest length in kW/m), denoted also as wave power, are provided by the wave model. The energy transport components are computed based on the next relationships:

$$\begin{aligned} Etr_x &= \rho g \iint c_x E(\sigma,\theta) d\sigma d\theta \\ Etr_y &= \rho g \iint c_y E(\sigma,\theta) d\sigma d\theta \end{aligned} \quad (2)$$

where $E(\sigma,\theta)$ is the directional wave energy density spectrum, x and y are the grid coordinate system (for the spherical coordinates x-axis corresponds to longitude and y-axis to latitude), and c_x, c_y are the propagation velocities of wave energy in the geographical space (absolute group velocity components) and g is the acceleration due to gravity.

Using the following relationship, the absolute value of the wave power is computed:

$$Etr = \sqrt{Etr_x^2 + Etr_y^2}. \quad (3)$$

Regarding the wind power, this can be evaluated based on the wind speed provided by various databases, at the reference height of 10 m above sea level. However, the tendency is to develop larger wind turbines operating at higher heights, to avoid the layers with turbulences to have a steady, consistent stream of wind power. For this reason, in each grid point the logarithmic law is applied following de next relationship [15]:

$$U_z = U_{z\,ref} \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}, \quad (4)$$

where U_z represents the wind speed value at the operational hub height z (with z=80 m in this work), U_{zref} is the wind speed corresponding to the reference height z_{ref} = 10 m above sea level and z_0 represents the surface roughness length. In various studies, an average value of 0.0002 m was considered, and this value is also adopted here [16, 17].

The information related to the energetic capacity of the wind is provided by the wind power density (P_{wind} in W/m^2), calculated with the following equation:

$$P_{wind} = \frac{1}{2}\rho_{air}(U_z)^3. \quad (5)$$

where ρ_{air} is the air density (an average value of 1.225 Kg·m^{-3} is considered) and U_z is that defined above [18].

A monthly analysis of the wave and wind power resources in the Black Sea, for the 30-year period 2021-2050 under RCP4.5 scenario, was made and the results concerning the months of February belonging to this time interval are presented in Figure 6. For such an analysis, the toolbox joints only the data corresponding to the month considered, computes the average value in each grid point over the indicated period and visualizes the results. As it can be noticed, the western part of the basin shows great potential for the extraction of both renewable resources, which was also highlighted in various studies [12, 19, 20].

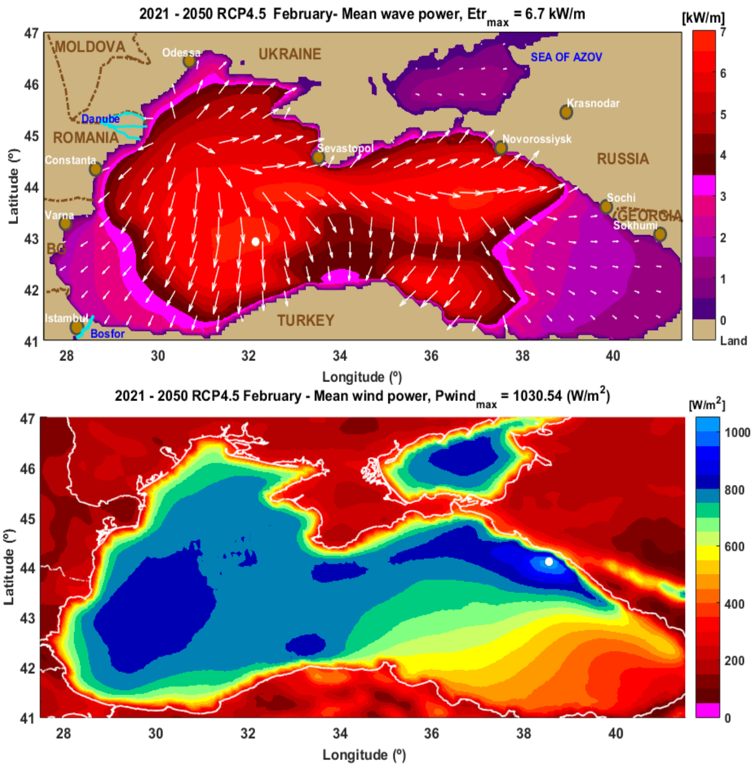

Fig. 6. Projections of the spatial distribution of the mean wave power field resulted from the SWAN simulations (top panel) and the mean wind power field (bottom panel), during the February months over a 30-year time interval (2021-2050) under RCP4.5 scenario.

3.2 Local analysis

Spatial analyses are very useful for an overview of environmental information from an ocean or sea basin, but for a study aiming at a restricted coastal area or a specific location, it is necessary to also perform a local analysis of the environmental matrix (wave/wind). In general, numerical models can provide as output the results at a certain position if the input file defines the geographical coordinates (longitude/latitude) of the targeted location and then the required parameters can be analysed. However, some locations of interest are often identified after a spatial analysis and then the researchers need to have the tools to extract the information about the environmental parameters without running the numerical models again, which would be highly time consuming, especially when the simulations cover several years.

Therefore, in the toolbox presented here, the facility to calculate the values of the parameters in a certain geographical location was included, using the interpolation methods available in Matlab. Thus, by comparing the information delivered by the model in a location with those provided by this tool that applies a 2D triangulation-based linear interpolation using the information available in the nodes of the computational grid, it was found that the values are very close.

Using long-term data available in a geographical location, analyses concerning the interannual variability of the average values of a certain wave parameter can be performed to indicate the trend of these values, among other information that we can obtain. To analyse the trend of the annual average values of Hs from a point located in the western part of the Black Sea basin, the Hs time series (with a temporal resolution of 3 hours) over an extended period (1987-2016) were analysed using the toolbox facilities and the results are shown in Figure 7. For the case presented, the linear trend adjusted to the annual means indicates an uprising tendency over the 30-year period analysed, while the superimposed five-year-running mean shows also some variability along the entire period.

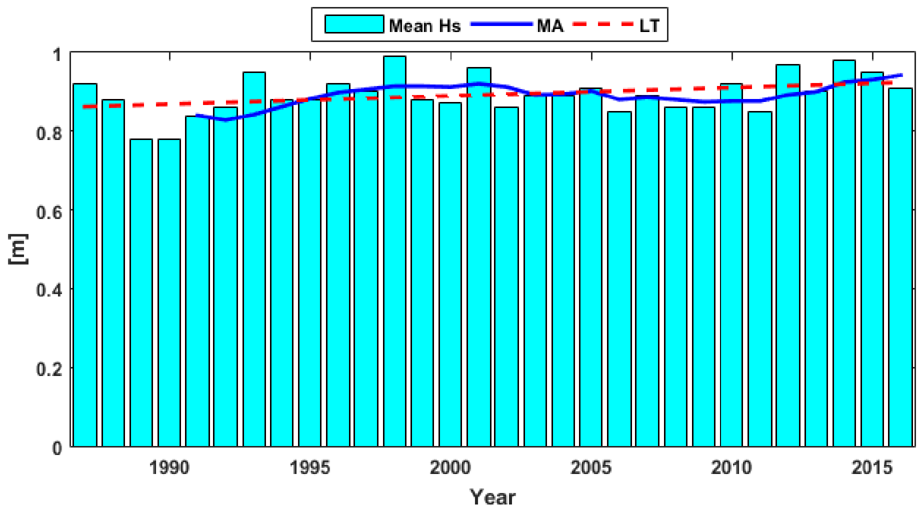

Fig. 7. Annual mean, five-year running mean (solid blue line) and linear trend (dashed red line) of Hs were computed for a location on the western side of the Black Sea.

Very useful for those who want to invest in the exploitation of wave energy are the bivariate distributions of the occurrences corresponding to the sea states from a location, using the significant wave height (*Hs*) and the wave energy period (*Te*). The bins considered for the sea states are 0.5 s×0.5 m (Δ*Te*×Δ*Hs*) and they have associated a colour according to a colourmap representing the number of occurrences, in percentage of the total. As an example, the scatter diagram presenting the bivariate distributions of the wave parameters above mentioned for a location near the Romanian coast (29.567°E/44.517°N) is presented in Figure 8. The deep water energy flux approximated with the following relationship is used to calculate and represent the wave power isolines [21, 22]:

$$Etr = \frac{\rho g^2}{64\pi} T_e H_s^2 \quad (6)$$

where ρ = 1025 kg/m3 is the density of the seawater.

It can be observed that the highest number of occurrences is in the vicinity of the isoline of 5 kW/m. Such diagrams provide an image of each sea state's contribution to the delivered wave energy by a wave energy converter (WEC), but the real wave power yield depends on the particular characteristics of each WEC device. This is rated by WEC's wave power generation (e.g. [23]) provided by the manufacturers as a function of *Hs* and a wave period.

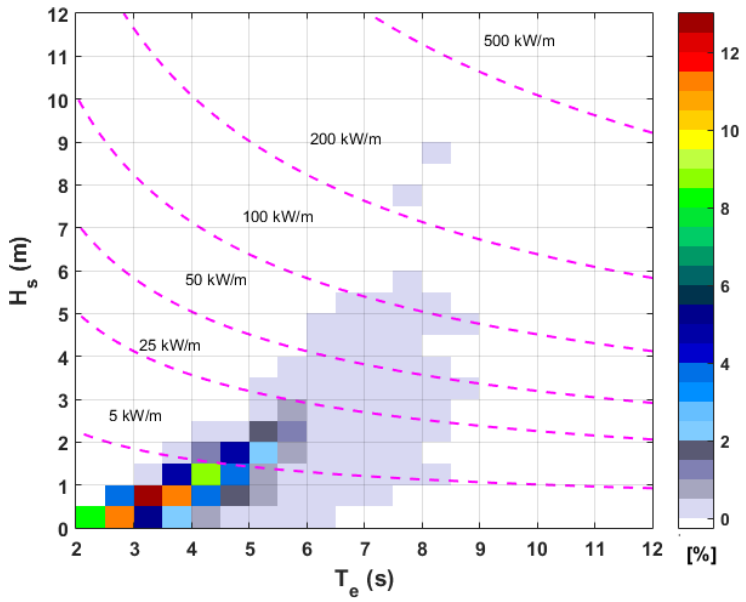

Fig. 8. Scatter diagrams (*Hs* against *Te*) for a point near the Romanian coast corresponding to the period 2071–2080, under RCP4.5 scenario.

3.3 Statistical analysis

In each point of the SWAN computational domain (in this case, being the Black Sea basin) time series with wave parameters are generated using the toolbox facilities. These time series are then used both for spatial and local statistical analysis, applying the functions already available in Matlab.

The variability of the sea state conditions (especially to estimate the impact of the extreme events in a time series) in a location can be evaluated using the higher moments, namely the skewness (Sk) and kurtosis (K). It is known that the areas with high values of kurtosis and skewness are in general affected by extreme *Hs* events [24]. Thus, these indexes can be evaluated based on the SWAN model results in each point of a computational domain (time series usually with 3 hours temporal resolution) for a time period, using the following relationships:

$$Sk = \frac{N^{-1}\sum_{i=1}^{N}(x_i - \bar{x})^3}{\sigma^3} \quad (7)$$

$$K = \frac{N^{-1}\sum_{i=1}^{N}(x_i - \bar{x})^4}{\sigma^4} \quad (8)$$

where x is the time series of the parameter analysed (usually is *Hs*), σ is the standard deviation, and N is the number of the size of the sample. The over bar denotes the average. When data cover a computational domain, N represents the number of the model output in each point of the domain over a time interval.

Data sets with high kurtosis (K>3) tend to have heavy tails, or outliers, while those with low kurtosis tend to have light tails or lack of outliers. Figure 9 shows the spatial distribution of the kurtosis indexes in the Black Sea, based on 30-year period of data analysed. As it can be seen there are extended areas where the kurtosis values are higher than 3.

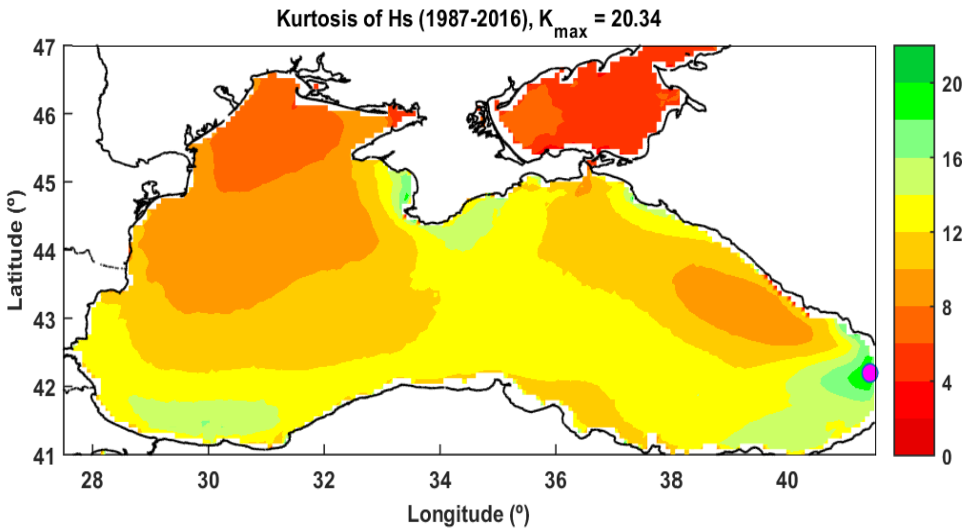

Fig. 9. Kurtosis of *Hs* for the 30-year period 1986–2016.

The time series of wave parameters in each point of the computational domain can be also used to compute the percentiles, which allow analysing of the data in terms of percentages. Thus, the 95th percentile indicates the value below which 95% of data is falling. Figure 10 illustrates the distribution of the 95th percentile of Hs computed for the 10-year period in the future. From this figure, it can be observed that the maximum value of 95th percentile is located in the western part of the Black Sea basin (marked with a white circle).

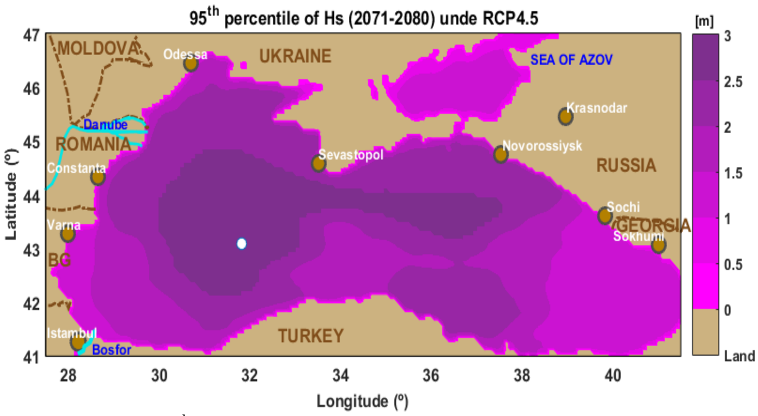

Fig.10. Distribution of the 95th percentile of *Hs* corresponding to RCP4.5 scenario for a 10-year time interval (2071-2080).

Another area in which it is important to know the sea state conditions over an extended period, as well as their dynamics, is the maritime transportation and shipbuilding, as well as the offshore industry. A facility offered by this toolbox is the ability to perform statistical analyses regarding the characteristics of the wave parameters and wind speeds along the maritime routes, with a special focus on the extreme values [25]. An example is shown in Figure 11, where the expected *Hs* 99th percentile values were calculated along the main Black Sea maritime routes for the future period 2021-2050 under RCP4.5 scenario.

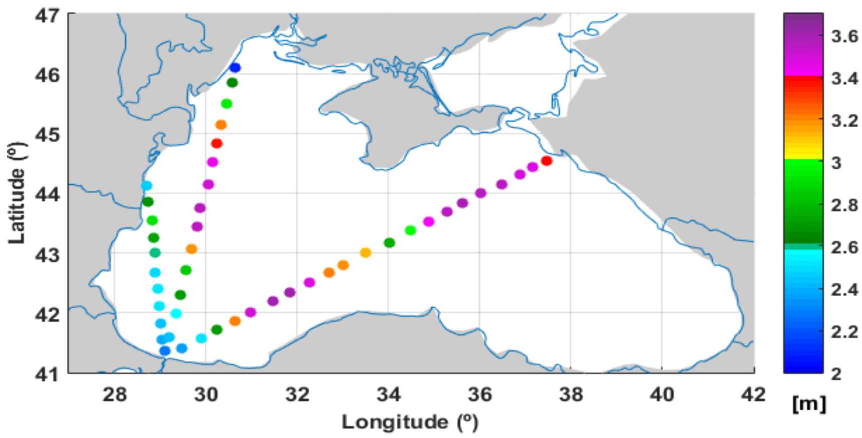

Fig.11. *Hs* 99th percentile along the Black Sea main maritime routes corresponding to RCP4.5 scenario for a 30-year time interval (2021-2050).

4. Conclusions

In this paper, the results obtained using a Matlab toolbox developed to provide numerical and graphical outputs for a quick assessment of the present and future wave and wind climate are presented. Based on wave and wind simulation data, quick information about the sea state or wind conditions (annual, seasonal and monthly statistics, trends, bivariate distribution of the wave parameters, wind speed magnitude), average wave and wind energy, analyses of the extreme events, over an area or in selected points or routes are provided as output.

Through the various examples presented here, it can be seen that the results delivered as graphical output (or even in numerical form) can represent useful information in various fields of activity related to the marine environment. This toolbox is now being integrated into the original computational platform WACA

Acknowledgment: This work was supported by a grant from the Ministry of Research, Innovation and Digitization, CNCS - UEFISCDI, project number PN-III-P4-PCE-2021-0015, within PNCDI III.

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