Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2024, Volume 12, Issue 2, 1110480

Original Research Article

An Analysis of the Environmental Matrix in the Adriatic Sea – Past and Future Projections

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Cite as: Rusu, L., An analysis of the environmental matrix in the Adriatic Sea – past and future projections, J.sustain. dev. energy water environ. syst., 12(2), 1110480, 2024, DOI: https://doi.org/10.13044/j.sdewes.d11.0480

ABSTRACT

The main objective of the proposed work is to assess the environmental matrix in the Adriatic Sea and its expected dynamics in the near future. The attention is focused on the analysis of the wind and wave climate in this basin and to perform a joint evaluation of the wind and wave power resources. The analysis is structured in two-time intervals, each one covering a 30-year time slice. The first time interval represents the past and covers the historical reference period 1976-2005, while the second comprises the near future from 2041 to 2070, under the Representative Concentration Pathway scenario 4.5. For the same two periods, the wave climate and the wave power were evaluated based on the simulation results carried out with the Simulating WAves Nearshore spectral phase averaged model. An analysis of the past and future expected extreme events is carried out. A comprehensive picture of the expected wind and wave power dynamics in the Adriatic Sea is provided by the comparison between the results obtained in the past with those from the near future. The synergy between the wind and wave power is also evaluated for future development of joint wind–wave projects. This option represents a viable direction for the near future to balance wind and wave power.

KEYWORDS

Adriatic Sea, Wave and wind climate, Average and extreme conditions, Wave and wind power, Past and near future.

INTRODUCTION

According to the analysis carried out by the International Energy Agency (IEA) [1], in the context of recent years marked by exceptional events, the global increase in CO_2 emissions was lower than anticipated. Furthermore, several countries returned to the use of coal (instead of natural gas) for the production of electricity and heat. It seems that the increased implementation of technologies based on clean energy has contributed substantially to preventing the accentuation of gas emission production, and an important contribution was made by the use of renewable energy sources [2], or by means of sustainable systems [3].

Since the potential of extending the production capacity of renewables on land has reached certain limits, in the last years the focus is on the marine environment because of its great potential both as an expansion in space and also from the point of view of renewable sources. The new strategy established in the framework of the 'European Green Deal' [4], highlighted the importance of offshore renewable energy (ORE).

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The offshore renewable energy has an important role in transforming the European Union into a low-carbon energy system and in achieving the very ambitious targets assumed. The decrease in renewable energy costs due to the maturity of the renewable energy technologies and the increase in energy demand gave an encouraging signal to exploit offshore renewable energy resources comprising various types according to the origin of the extracted power [5]. Many European countries have coastal areas where the exploitation of these resources can be done efficiently. However, various obstacles, including the complex legal framework that applies to ORE projects [6], have made their development slower, with the sole exception represented by offshore wind, which had a spectacular advance in the last three decades.

The Atlantic coast of Europe represents a very attractive environment for the exploitation of offshore renewable energy due to the considerable resources available. The evaluation of the offshore wind potential was made by several studies covering various Atlantic coastal regions. Thus, using high-resolution wind fields, the offshore wind potential over a 10-year period was assessed along the Atlantic Iberian coast [7] and the dynamics of these resources were evaluated [8]. An overview of these resources along the European coasts for the present climate conditions and their evolution in the future was made, with the purpose to identify the optimal locations for installing offshore wind farms [9]. The efficiency of the offshore wind farms already installed in various areas such as the North Sea [10] or the Baltic Sea [11], gave an impetus to the development of this sector [12]. Of course, when installing them, various aspects must be taken into account, as presented in [13]. Such resources are a solution for the energy independence of isolated areas, as is the case of the islands in general [14], and for sustainable energy solutions in these areas [15]. An example is the preliminary study developed for the small islands of the Mediterranean Sea [16].

On the other hand, wave energy presents a remarkable potential shown at the global level by [17], that so far has not been exploited due to the slow evolution of its harvesting technologies [18]. An up-to-date review of the methods used to assess the wave energy resources at several scales is presented in [19]. Until now, various technologies with different conversion efficiencies have been developed [19], but none could stand out enough to be used for large-scale implementation. Recently, a new method to assess the wave energy converters' performance was developed [20]. For the efficiency and maximization of the performance of the wave farms, a very important issue is the optimization of the wave energy converters (WECs) arrays [22]. Also, the implementation of hybrid energy farms represents a viable solution to reduce the variability of resources [22], as well as to optimize the amount of energy sent to the energy system [23]. On the west Iberian coast, the implementation of such hybrid solutions or co-located wind-wave farms represents a feasible solution taking into consideration the significant wind and wave resources [25].

In general, WECs have been designed for ocean waves with higher energy potential, and the quantity of energy they could capture shows promising values. But, because in the oceans they are exposed to severe events that have a higher intensity and frequency than in small sea basins, their lifespan reduces, and the maintenance costs are higher. That is why, in recent years, attention has also started to be directed towards the evaluation of renewable resources in the European seas, such as the Mediterranean Sea [26] or the Black Sea [27]. The dynamics of the wave power in the Black Sea basin until the end of this century was also evaluated [28]. Various studies indicate that, although the mean wave power in these semi-enclosed seas does not show very high values, there are still advantages such as simpler and safer maintenance, and lower location costs. Furthermore, the fact that the tidal variation is low compared to the ocean helps even more [29].

In general, the technologies developed so far have not been oriented towards the exploitation of the waves with a milder regime, and this leads to the consideration of the areas with such a wave regime as not being competitive for the development of wave energy exploitation projects. However, recent studies indicate that the extraction of wave energy in seas with mild resources [30], such as the Mediterranean Sea [31] can be efficient. In addition, the fact that, in many areas characterized by mild waves, there are areas where the wind speed presents excellent characteristics for the efficient exploitation of its power must be also taken into account [32]. In such areas, there is the possibility of implementing hybrid projects for the joint of wave and wind energy extraction [33], by applying optimized assessment methods to find locations for such combined wave and offshore wind projects [34]. A review of the most important aspects to be taken into consideration in the implementation of the combined wave and offshore wind energy systems is presented by [35].

From this perspective, within this study an analysis of the wave and wind power potential will be carried out in an isolated area of the Mediterranean Sea, which separates the Italian Peninsula from the Balkan Peninsula, and where some of the conditions described above regarding the wind and wave regime are found. Thus, the target area of the present work is the Adriatic Sea, identified as a potential hot-spot for offshore wind farm development [36]. For example, feasibility studies indicate that the northern part of the Adriatic Sea is suitable for the development of a large wind farm [37]. Regarding the wave power, the exploitation potential is lower considering that swell is less present in this basin [38]. However, recently various prototypes of WECs were tested in the South Adriatic Sea [39], and offshore Montenegro [40], which indicates that, with a device designed to be suitable for mild wave conditions, there is the possibility of producing energy efficiently.

Considering the current context in which the impact produced by climate change on weather conditions is more and more evident, the objective of the present work is to evaluate both components of the environmental matrix (wind and wave) in the Adriatic Sea. Two-time intervals, each one covering a 30-year time slice, are considered in the analysis. The first time interval represents the past and covers the historical reference period 1976-2005 when both wind fields from ERA5 (abbreviation of ECMWF RE-analysis, fifth generation [41]) and those produced by the Regional Climate Models (RCMs) are considered. The second period comprises the near future from 2041 to 2070, under the Representative Concentration Pathway scenario 4.5 (RCP4.5). Based on these wind fields, the wind climate over the Adriatic Sea and the offshore wind power is evaluated. The same wind fields are used to force a wave model to assess the wave climate and also the wave power. The expected dynamics of the environmental matrix for the near future against the historical period are estimated by comparing the results obtained for each time interval considered. To the best of our knowledge, such a study of both marine renewable energy resources, based on high-resolution data covering the recent past period and the near future, has not been carried out yet in the Adriatic Sea basin.

MATERIALS AND METHODS

This section describes the wave modelling system implemented to simulate the sea state conditions in the Adriatic Sea and the wind datasets used to drive the wave model. Then, the environmental matrix in the target area is evaluated. The methods to assess wind and wave power, and the climate change impact on these renewable resources are also discussed.

Datasets

The basin of the Adriatic Sea is part of the Mediterranean Sea and is connected to it through the Strait of Otranto. Because the sea state conditions from the Mediterranean Sea influence the waves near the connection area between the two seas, a two-level system for the wave simulations in the Adriatic Sea is implemented. The entire basin of the Mediterranean Sea represents the first level of the wave modelling system, and it is used only to provide boundary conditions for the second level, which is focused on the Adriatic Sea (see Figure 1). The wave model considered is SWAN model (Simulating WAves Nearshore, version 41.31AB [42]), a state-of-the-art wave model based on the spectrum concept, which has been implemented with good results both in the Mediterranean Sea [43], [44] and in other basins comparable to the

Adriatic Sea [45]. The computational domain covering the Mediterranean Sea has a spatial resolution of 0.2° in both directions, while the second domain has a resolution of 0.1°.

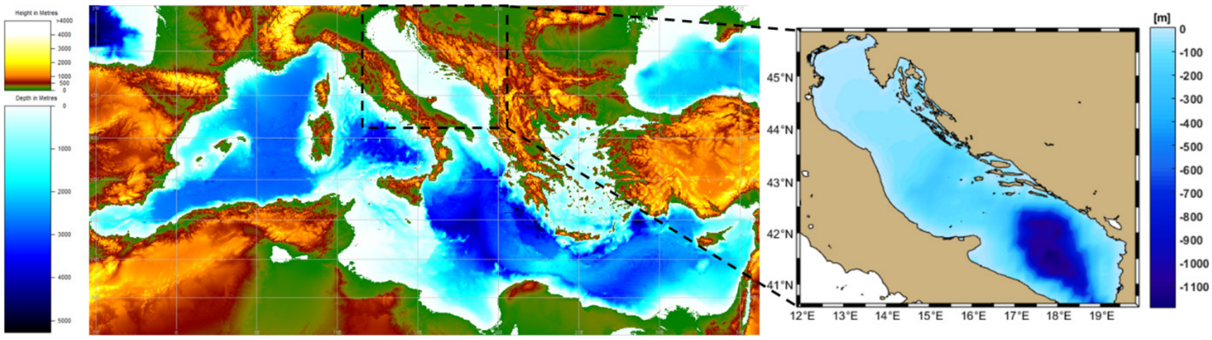


Figure 1. The computational domains of the SWAN simulations

In all simulations, for the spectral space, 36 directions and 30 frequencies (from 0.04 Hz to 1 Hz with logarithmic increment) were used. The SWAN model was run in the non-stationary mode, with a 10 min for the time step and the iteration number was set to 4 (default is 1). A new source term formulation implemented recently in SWAN (denoted as ST6 [46]), together with the new option for the non-breaking dissipation of Ardhuin *et al.* [47] were used. This option was implemented with good results in semi-enclosed basins [48] and at the ocean scale [49].

For the historical reference period 1976-2005, hindcast simulations were first carried out, when ERA5 wind fields with a spatial resolution of 0.25° and temporal resolution of 3 hours (the last reanalysis data provided by the European Centre for Medium-range Weather Forecast - ECMWF) were used to force of the wave modelling system. These results delivered by the wave modelling system in the Mediterranean Sea were validated by performing a comparison of the simulated significant wave heights (*Hs*) with altimeter measurements and the statistical parameter values confirmed a very good agreement between the measured and simulated *Hs* values. The second set of simulations for the reference period 1976-2005 was made by forcing the wave modelling system with historical high-resolution wind fields (0.11°) simulated at SMHI (Swedish Meteorological and Hydrologic Institute) with the Rossby Centre regional atmospheric model (version RCA4 [50]) and provided for public access through EURO-CORDEX database [51].

For the near future period (from 2041 to 2070), the wind fields considered to drive the wave modelling system are those simulated by the same RCM, namely RCA4, under RCP4.5 emission scenario. All wind fields simulated by RCA4 and used in this study have a temporal resolution of 6 hours. Like all the wind fields provided by EURO-CORDEX, they also cover entire Europe, being used in various studies, e.g. [52].

Environmental matrix in the Aegean Sea

For the evaluation of the wave climate and wave power corresponding to the recent past (historical period) and near future in the Adriatic Sea, the results provided as output at the second level of the SWAN model are used. Thus, at each point of the computational domain, 3-h resolution time series of the various wave parameters are generated and further, based on this information the wave climate and wave power assessment are designed.

In this study, the attention is directed especially to the analysis of the main wave parameter, namely *Hs*, and also to the wave power (or wave energy transport) *Etr*. SWAN provides as output the wave energy transport components (i.e. energy flux per unit of the wave crest length in kW/m). The relationships implemented in SWAN to compute the wave transport components are:

$$Etr_{\mathrm{x}} = \rho g \iint c_{\mathrm{x}} E(\sigma,\theta) d\rho d\theta$$
$$Etr_{\mathrm{y}} = \rho g \iint c_{\mathrm{y}} E(\sigma,\theta) d\rho d\theta \text{ ,} \tag{1}$$

where $E(\sigma,\theta)$ is the directional wave energy density spectrum, x and y are the spherical grid coordinate system (longitude and latitude), and c_{x}, c_{y} are the propagation velocities of wave energy in the geographical space (absolute group velocity components).

The absolute value of the wave power in each point of the computational grid is calculated with the following relationship:

$$Etr = \sqrt{Etr_{\mathrm{x}}^2 + Etr_{\mathrm{y}}^2} \tag{2}$$

The SWAN hindcast driven by the ERA5 wind reanalysis dataset is used as a reference. Then, they are compared with the SWAN historical results when the wave model is forced by the RCA4 historical wind dataset. This comparison assesses the capability of the SWAN historical data to reproduce the recent past wave climate and corresponding wave power fields. The results are presented as normalized differences (*ND*): the difference between the historical data (*CD* - when the RCA4 climate dataset is used) and the hindcast data (*ER* - when ERA5 reanalysis dataset is used) means, divided by the hindcast means (*ER).*

$$ND = \frac{\overline{CD}-\overline{ER}}{\overline{ER}} \times 100 \tag{3}$$

In order to analyse the dynamics induced by climate changes on the significant wave height and wave power means along the 21st century under RCP4.5 scenario, the relative change (RC) index was computed as the difference between the near future (2041-2070) and recent past (1976-2005) means, divided by recent past means, i.e.,

$$RC = \frac{\overline{NF}-\overline{RP}}{\overline{RP}} \times 100 \tag{4}$$

where $\overline{RP}$ represents the mean wave power or mean *Hs* over the recent past period and $\overline{NF}$ is the mean wave power or mean *Hs* over the near future period. *RC* values are given as a percentage relative to the recent past period.

For the evaluation of the wind climate, it is well known that the wind fields distributed by the databases, which are used in forcing the wave models, are simulated at a typical height of 10 m above sea level. However, for the evaluation of the wind power potential in a certain area, it is necessary to use the wind speed at a height corresponding to that at which the wind turbines are installed. Nowadays, the tendency is to develop larger wind turbines installed at heights that reach 100 m and for this reason, this height will be considered as a reference for the analysis made in the present study regarding the wind climate and wind power. Thus, in each grid point, the logarithmic law is applied following the next relationship established by [53], [54]:

$$U_{100} = U_{10} \frac{\ln z_{100}/z_0}{\ln z_{10}/z_0} \tag{5}$$

where U_{100} represents the wind speed at 100 m height, U_{10} is the wind speed at 10 m height, z_{100} is the operational height (100 m) and z_{10} is the reference height of 10 m, respectively. The surface roughness length is denoted with z_0, and an average value of 0.0002 m is considered in the present work.

Another important parameter evaluated in this study is the wind power density P_{w} (W/m^2) per unit of the swept area, computed based on the information regarding the wind speed at the installed height of the wind turbine (in this case 100 m) using the relationship:

$$P_{\mathrm{w}} = \frac{1}{2}\rho_{\mathrm{air}}U_{100}^{3}, \tag{6}$$

with ρ_{air} the air density has the value of 1.225 kg/m^3.

As in the case of the waves, to assess the capability of the RCA4 model to reproduce the recent past wind fields and corresponding wind power, the normalized differences (*ND*) were calculated. Then, in order to assess the dynamics induced by the climate changes on the wind speed (U_{100}) and on the wind power density means along the 21st century under the RCP4.5 scenario, the relative change (*RC*) index was also computed.

RESULTS

In this section, an evaluation of the wave and wind climate, as well as of the wave and wind power, is carried out considering both data from the recent past and the near future. This includes analyses of the annual and seasonal means. Furthermore, the expected dynamics of the parameters analysed along the 21st century is also performed by comparing the results from the near future with the historical data.

The SWAN model produces simulated results at each point of the computational domain, with a temporal resolution of 3 hours. The average value of the parameter analyzed (either *Hs* or *Etr*) at a point is obtained by averaging the corresponding time series. After that, having the average values computed at each point of the grid, the spatial distribution of the values is constructed and visualized as maps. The seasonal means of the parameters are evaluated following the World Meteorological Society seasonal partition: December-January-February (DJF - winter), March-April-May (MAM - spring), June-July-August (JJA - summer) and September-October-November (SON - autumn). Using these data corresponding maps for each season are also designed. The geographical location of the maximum value in the field is illustrated on the map (marked with a white circle).

Wave and wind climate

The mean significant wave height fields (*Hs*) resulting in the Adriatic Sea, based on the hindcast simulations, are illustrated in **Figure 2a**, while those for the historical simulations are presented in **Figure 2b**. As above mentioned, for the hindcast simulations, the ERA5 wind fields were used to force de SWAN model, while for the historical simulations, the RCA4 wind fields were considered. A visual evaluation of the two maps shows a similar pattern in both fields, with the highest values in the southern part of the basin, reaching maximum values of 0.8 m (located very close to the southern border of the domain where the connection is made with the Mediterranean Sea) and 0.87 m, respectively. In general, the enclosed and semi-enclosed seas are characterized by a limited fetch for wave development and these features prevent waves from travelling for long distances and generating swell. For this reason, in such basins, sea waves with lower wave periods characterise the wave climate. However, under the Bora wind, it is possible, and relatively frequent in the Adriatic Sea, to be generated waves with *Hs* higher than 10 m, as mentioned by Cavaleri *et al.* **[55]**. The presence of higher *Hs* means in the southern part of the Adriatic Sea is explained by the influence of the waves penetrating from the Mediterranean Sea.

The normalized differences of the two *Hs* fields, computed as indicated in eq. (3), are illustrated in **Figure 2c**. Over the entire basin, the historical *Hs* means present higher values, with extended areas showing a general rise of about 20%. There are a few small areas with excessive increases (reaching 40%) but they are located near the coast, and this is influenced by the different resolutions of the wind fields used to drive the wave model. The ERA5 wind fields, having a lower resolution, cannot capture accurately the wind speed changes (in magnitude and direction) in the coastal areas, this being also influenced by the complicated coastal orography that surrounds the Adriatic Sea **[56]**. In the coastal zone of Croatia, where many small islands are present, small decreases (up to 10%) of the *Hs* means are noticed. This can be caused by the fact that the bathymetry used is not fine enough to take into account all the small islands and then the effect induced by their presence is not represented by the model results. A new level of the wave modelling system should be added, using a very high-resolution bathymetry, if the interest is focused on that coastal zone.

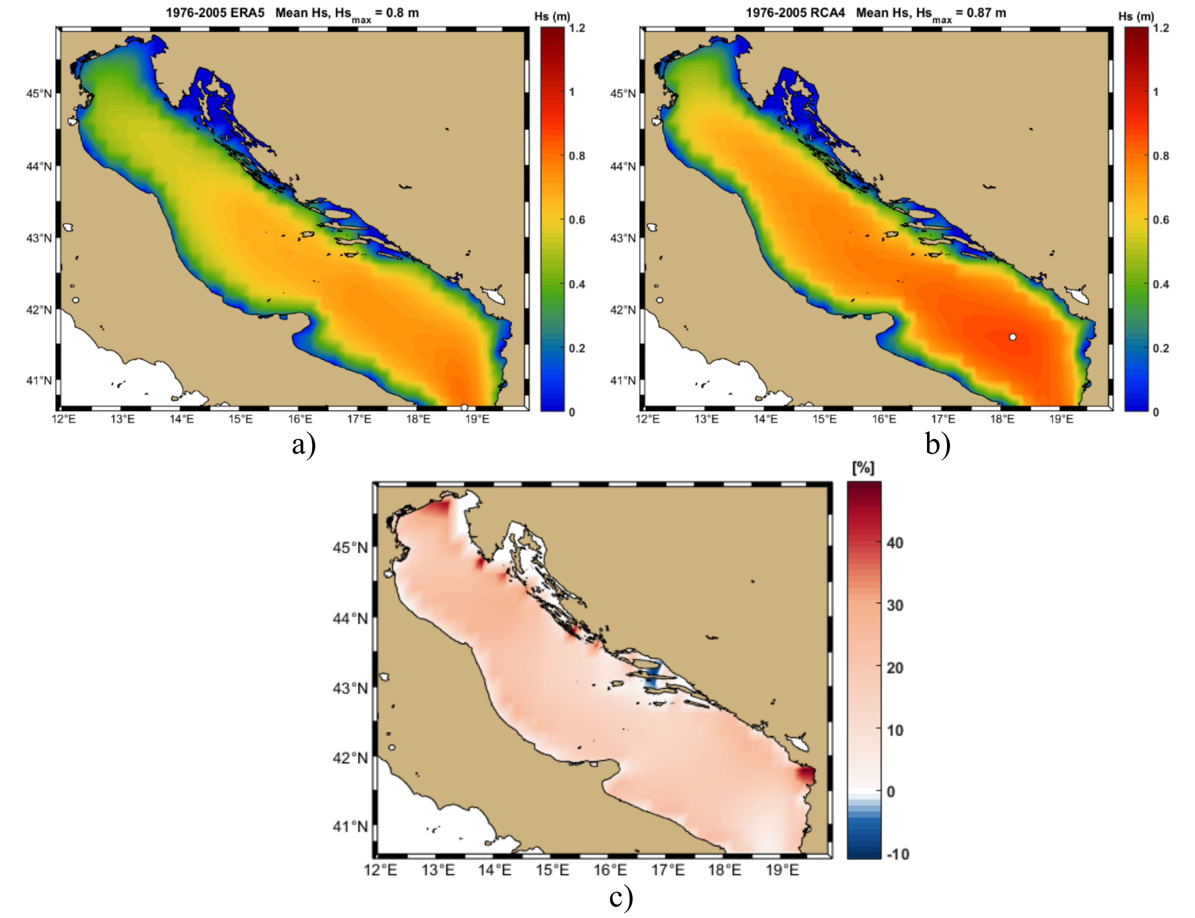


Figure 2. Average values of *Hs* for the recent past 1976-2005: a) SWAN forced with ERA5 wind fields; b) SWAN forced with RCA4 wind fields; c) normalized differences (*ND*) between the two *Hs* fields

The seasonal characteristics of the average *Hs* values are evaluated and presented in **Figure 3**, and the corresponding normalized differences are illustrated in **Figure 4**. From top to bottom, the panel rows from **Figure 3** show the maps of the mean *Hs* spatial distribution in the Adriatic Sea for DJF, MAM, JJA and SON. On the left side of **Figure 3**, the results corresponding to the hindcast simulations are presented, while on the right side those for the historical simulations.

In all seasons the maximum values of the *Hs* means are higher in the case of the historical simulations, as can be seen in **Figure 3**. For each type of result (hindcast or historical), the geographical positions of the maximums do not change significantly compared to the corresponding ones illustrated for the average fields computed over the entire period. The seasonality of the wave climate in the Adriatic Sea is clear, showing in the transition seasons (spring - MAM and autumn - SON) similar average values for *Hs* (with maxima located in the range of 0.8-0.93 m), while the values in the winter are almost double compared to those simulated during the summer season (1.04 m and 1.14 m, compared with 0.54 m and 0.6 m respectively).

Regarding the normalized differences shown in **Figure 3**, they have higher values (both positive and negative) in the warmer season (summer) and decrease as the analysis of *ND* moves towards the colder seasons. In the northern part of the basin, the results of the historical simulations indicate increases in the *Hs* averages of approximately 40% compared to the results of the hindcast simulations, while in the summer similar increases are indicated along the eastern coast of the basin. In very small areas negative *ND* values are found, without exceeding decreases of about -14% encountered in summer.

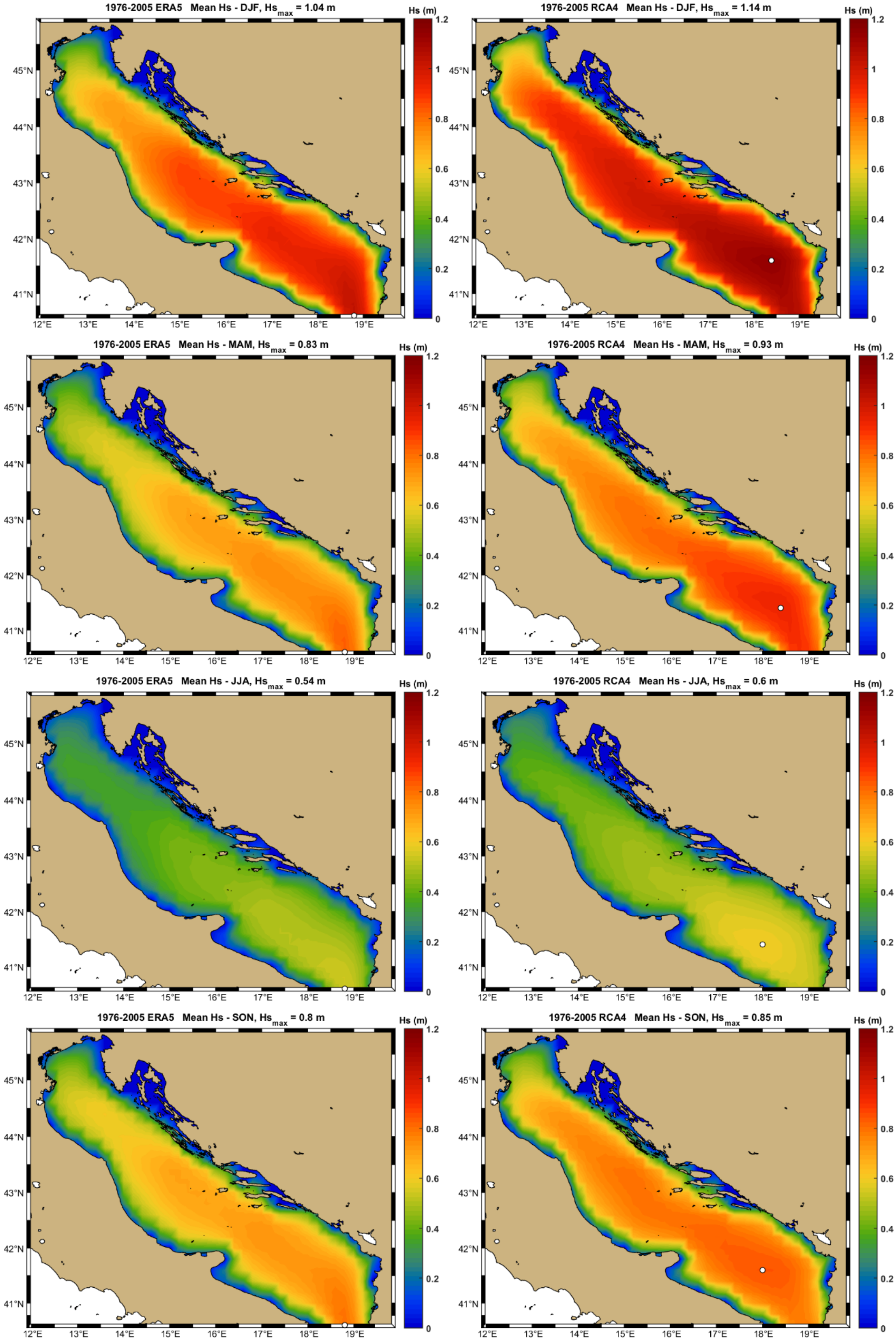


Figure 3. Seasonal average values of the significant wave height for the recent past (1976-2005): results from SWAN forced with ERA5 wind fields – left panels; results from SWAN forced with RCA4 wind fields – right panels

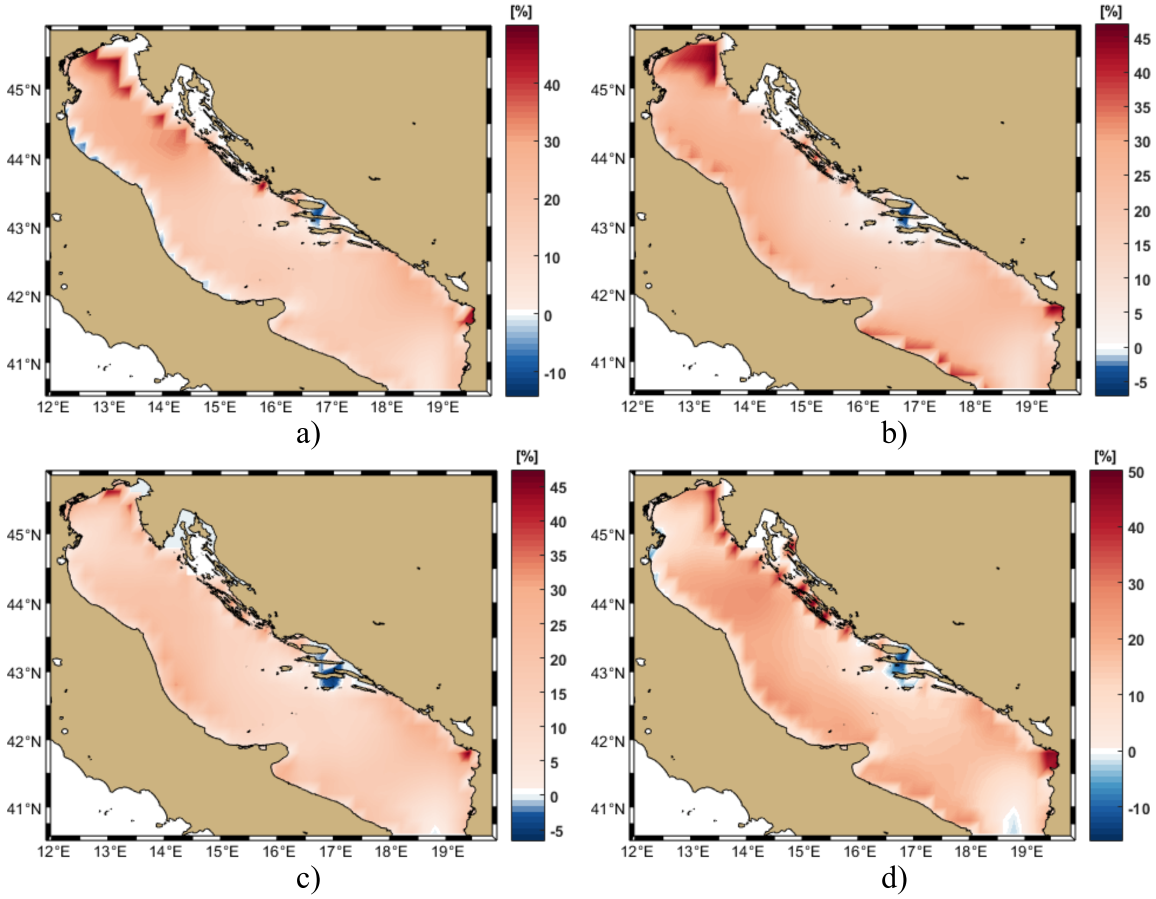


Figure 4. Seasonal normalized differences (*ND*) between the average values of *Hs* for the recent past 1976-2005: a) DJF, b) MAM, c) JJA and d) SON

The next step is to evaluate the changes of the mean *Hs* values for the near future computed as a percentage relative to the historical period, denoted also in eq. (4) as the recent past (*RP*).

The relative change values in terms of mean *Hs* computed for the entire period are presented in **Figure 5**, while those for each season are illustrated in **Figure 6**. In the near future, the decreases in *Hs* means are envisaged in the northeastern part of the Adriatic Sea, the decrease being more pronounced in the northern part (about 4.8%). This pattern was identified also in a previous study [57] under the IPCC A1B emission scenario. In the southeastern side, the decrease is ranging from 0.5 to 2%, while in the centre part of the basin, very small changes are noticed (increases of about 0.5% in the west-central zone and decreases of about 0.5% in the east-central area).

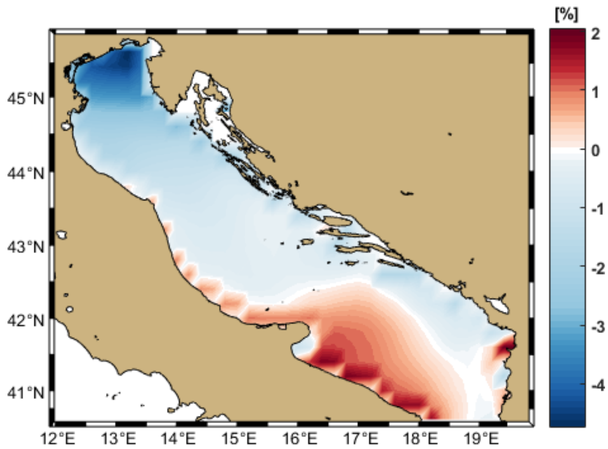


Figure 5. Changes of the mean *Hs* as a percentage relative to the recent past period for the near future corresponding to the RCP4.5 scenario

The pattern of the *RC* values shows some changes from one season to another (see **Figure 6**), but in the northern area of the basin, the average *Hs* values decrease always in the near future. These decreases are more accentuated and cover larger areas (north and southeast of the basin) during spring when they reach 6.5% in the north, followed by winter when negative *RC* values are noticed in the all-northern half of the basin (the highest decrease being around 5.6% in the north of the Adriatic Sea). An opposite *RC*'s trend is expected during the summer. Thus, in the southwest of the basin positive values of *RC* are found (reaching 5.8%) indicating an increase of the *Hs* average values in the near future, while in the northeastern side of the basin, *RC* negative values up to 18% are encountered, which indicates decreases of the *Hs* average values.

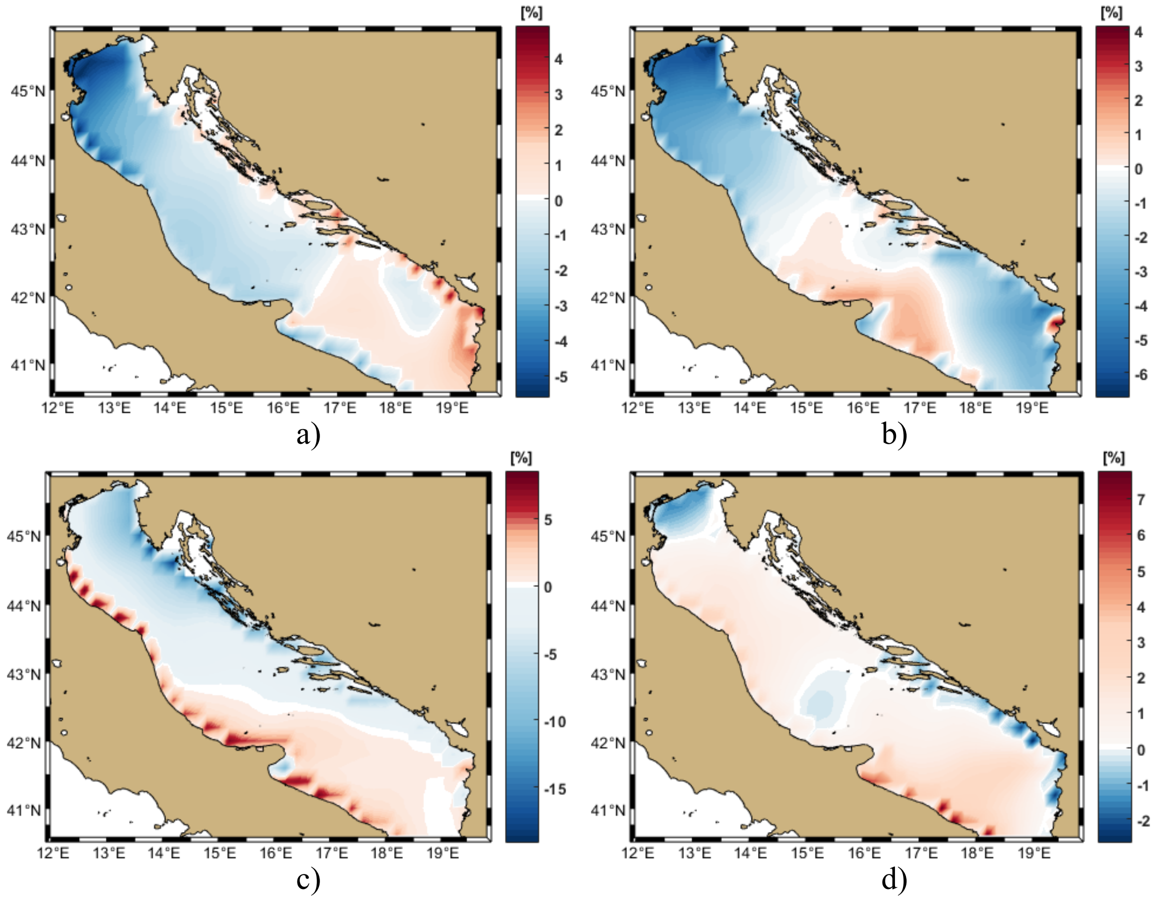


Figure 6. Seasonal changes of the mean *Hs* as a percentage relative to the recent past period for the near future corresponding to the RCP4.5 scenario: a) DJF, b) MAM, c) JJA and d) SON

The mean wind climate over the Adriatic Sea at 100 m above the sea level, obtained by applying the relationship from eq. (5) to ERA5 and RCA4 datasets for the recent past period, is illustrated in **Figure 7a** and **Figure 7b**, respectively. The maximum values of both mean wind fields are 7.5 m/s for ERA5, and 7.4 m/s for RCA4. According to these results, the wind climate has a similar pattern for both datasets. Higher values of RCA4 data are noticed in the northwestern and southeastern parts of the basin, as indicated by the normalized differences (*ND*) between the two fields illustrated in **Figure 7c**.

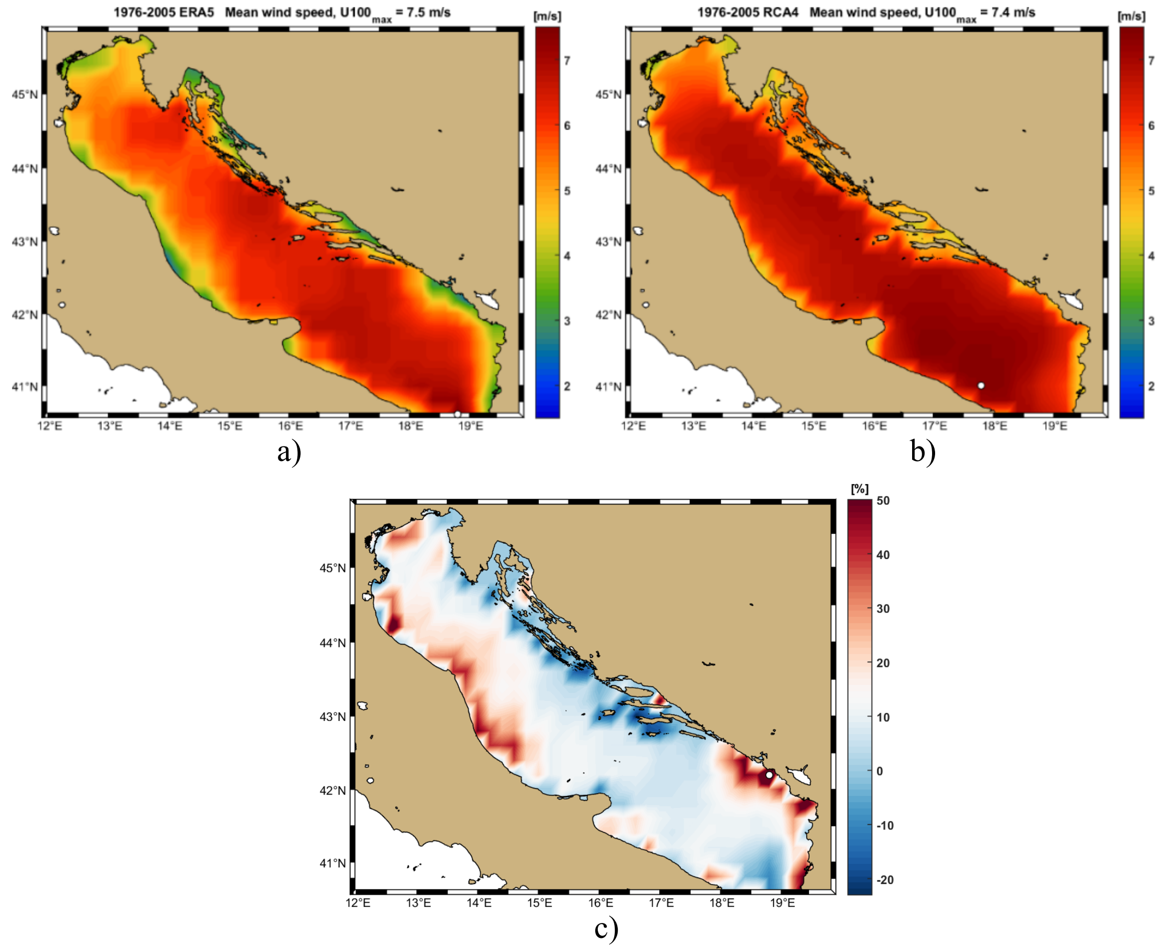


Figure 7. Average values of U_{100} for the recent past 1976-2005: a) ERA5 wind fields; b) RCA4 wind fields; c) normalized differences (*ND*) between the two fields

The projections of the mean wind speed U_{100} for the near future period are given in **Figure 8a**, while the changes in the mean U_{100} values for the near future, computed as a percentage relative to the historical period, are illustrated in **Figure 8b**. For the near future, the expected *RC* values have small variations over the Adriatic Sea, ranging from -3.8% to 2.2%, with positive values in the southern part of the basin.

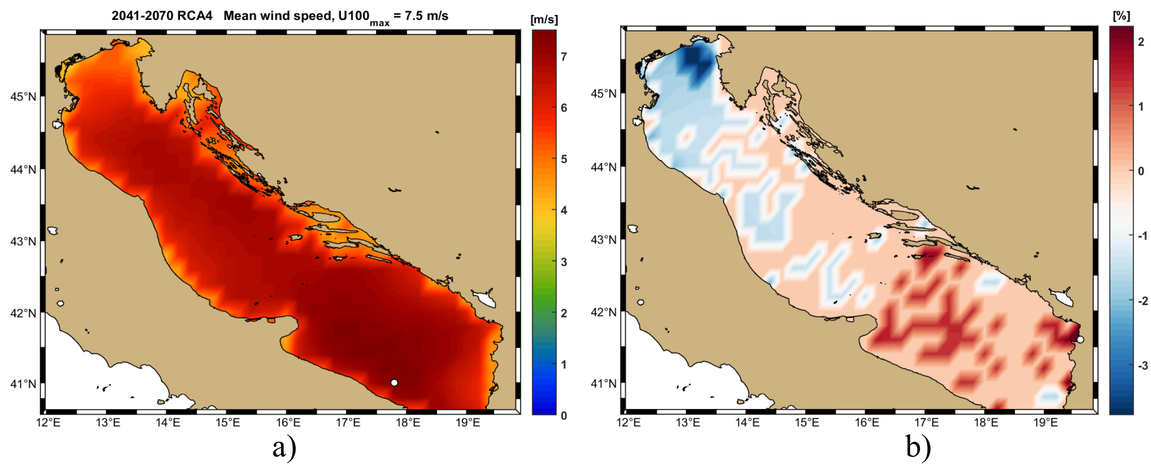
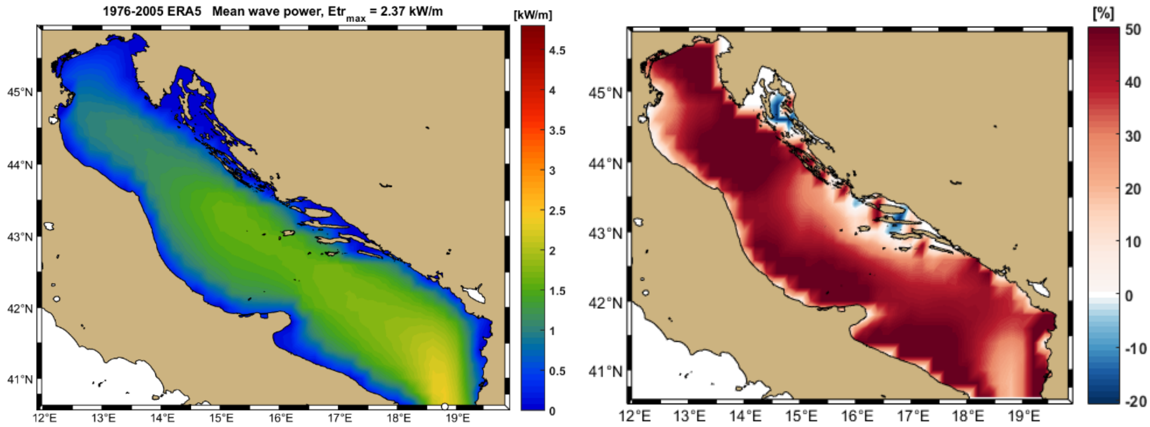


Figure 8. a) Average values of U_{100} for the near future 2041-2070; b) Changes of the mean U_{100} as a percentage relative (*RC*) to the recent past period for the near future corresponding to the RCP4.5 scenario

Wave and wind power

The wave power (*Etr*) results obtained as an output of the SWAN model driven by ERA5 (see **Figure 9a**) and RCA4 wind fields (not shown here) for the recent past period have maximum values of 2.37 and 2.8 kW/m. These fields are compared using the normalized differences and the results are illustrated in **Figure 9b**. As expected, the historical wave power presents higher values than those simulated using ERA5 data. The normalized differences can reach values of almost 50% over extended areas.



a) b)

Figure 9. a) Average values of *Etr* for the recent past 1976-2005 based on SWAN results forced with ERA5 wind fields; b) normalized differences (*ND*) between the recent past data

From the average values of the wave energy calculated for each season, it can be seen that there is a drastic reduction in it during the summer (see **Figure 10**), compared with the other seasons. The wave power from the Adriatic Sea does not have high values (especially in the northern part of the basin) compared with wave energy resources encountered in the ocean coastal areas, but through joint exploitation with other renewable sources available in the marine environment, it can represent however a source of reducing the variability of the renewable energy for the integration to the power system **[58]**.

Some projections regarding the dynamics of wave energy in the near future under the RCP4.5 emission scenario are presented in **Figure 11**, and the results indicate a tendency of reduction of the wave energy in the northwest part by up to 8%. In the south-eastern part of the sea, an increase in terms of wave power of up to 10% is estimated over extended areas.

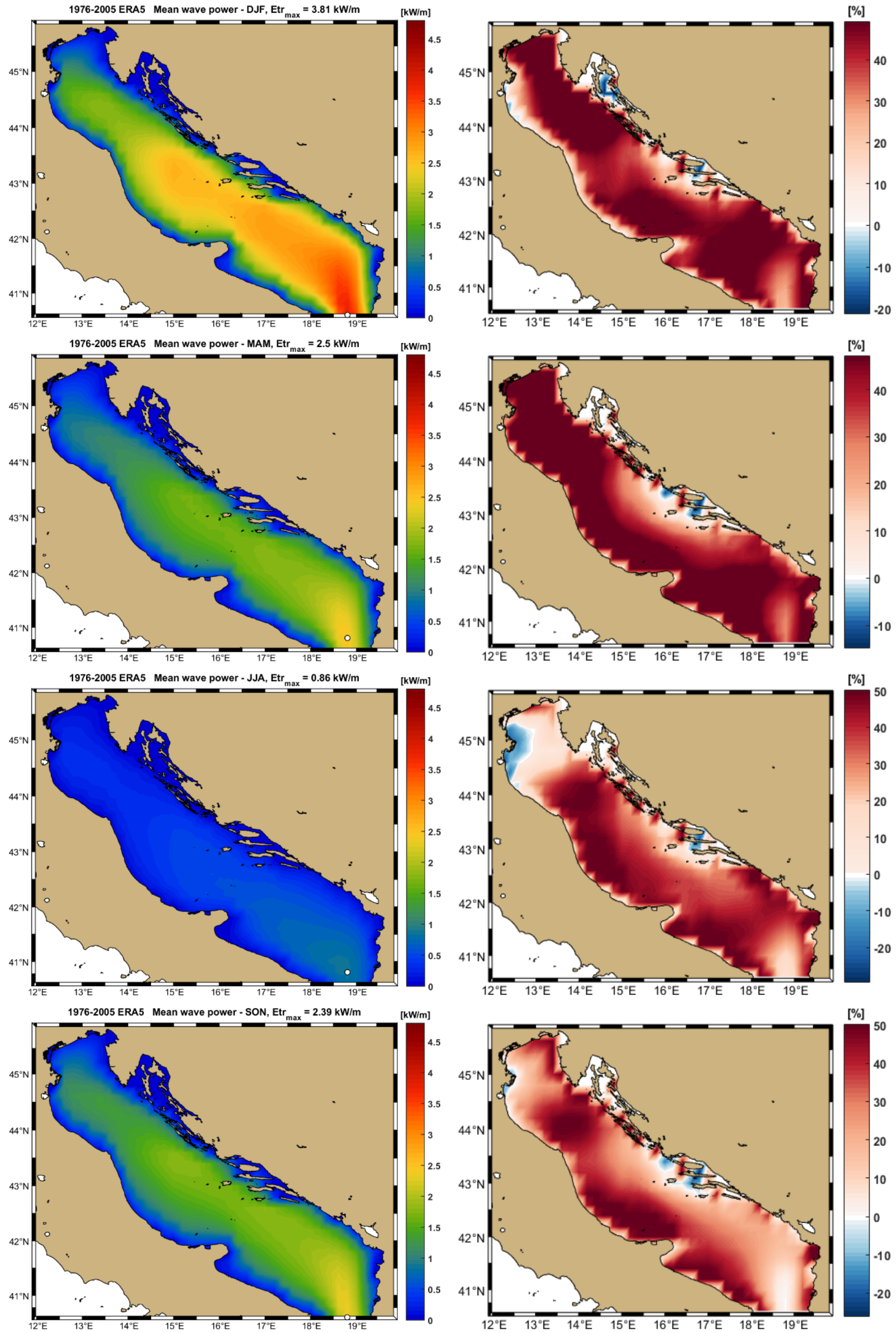


Figure 10. Seasonal average values of wave power for the recent past (1976-2005): results from SWAN forced with ERA5 wind fields – left panels; normalized differences (*ND*) between the recent data – right panels

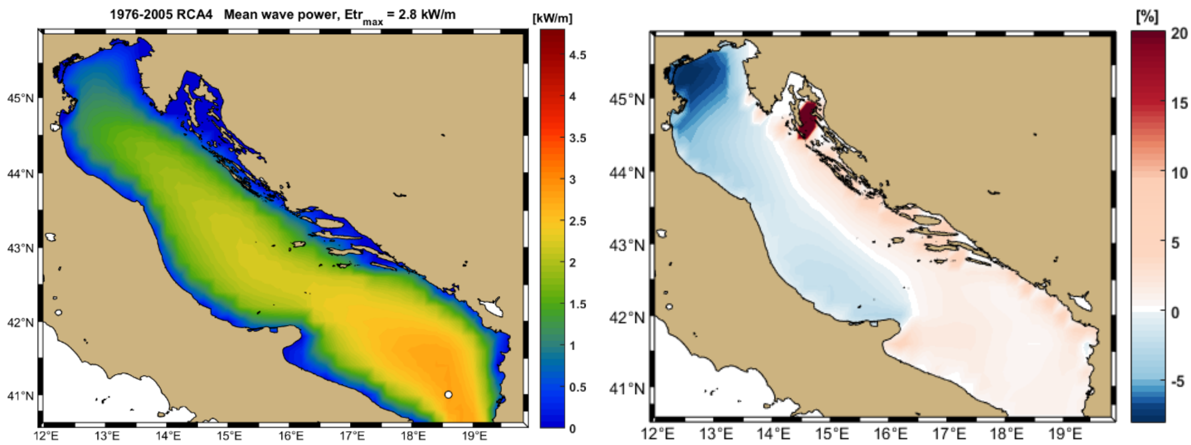


Figure 11. a) Average values of *Etr* for historical data, results from SWAN forced with RCA4 wind fields; b) Changes of the mean *Etr* as a percentage relative to the historical period for the near future corresponding to the RCP4.5 scenario

The seasonal analysis of the wave power dynamics in the near future is presented in **Figure 12**. Autumn appears to be the period when, in most of the basin, wave power increases of up to 8% are expected. In the other seasons, the areas where wave power growths occur are moving across the basin from season to season, but the increases are not found in the northern area.

The Adriatic Sea has many coastal areas where shallow water depths are found, which would facilitate the deployment of the offshore wind farm projects. For this reason, the assessment of these resources and their dynamics in the near future is important. Next, an analysis of the offshore wind power density (P_w) will be carried out to evaluate its potential. Thus, the average values of the wind power density are calculated based on the wind speed at 100 m and their spatial distribution over the Adriatic Sea is illustrated in **Figure 13**.

The maximum values calculated for P_w based on the two sources of wind speed (ERA5 and RCA4) for the recent past indicate values close to 500 W/m^2 over the southern part of the basin. The normalized differences (*ND*) between the results obtained using the two sources are small, showing a maximum of around 4% higher values for RCA4 in the southern part of the basin and around 6.5% lower values for RCA4 in the northern area of the basin.

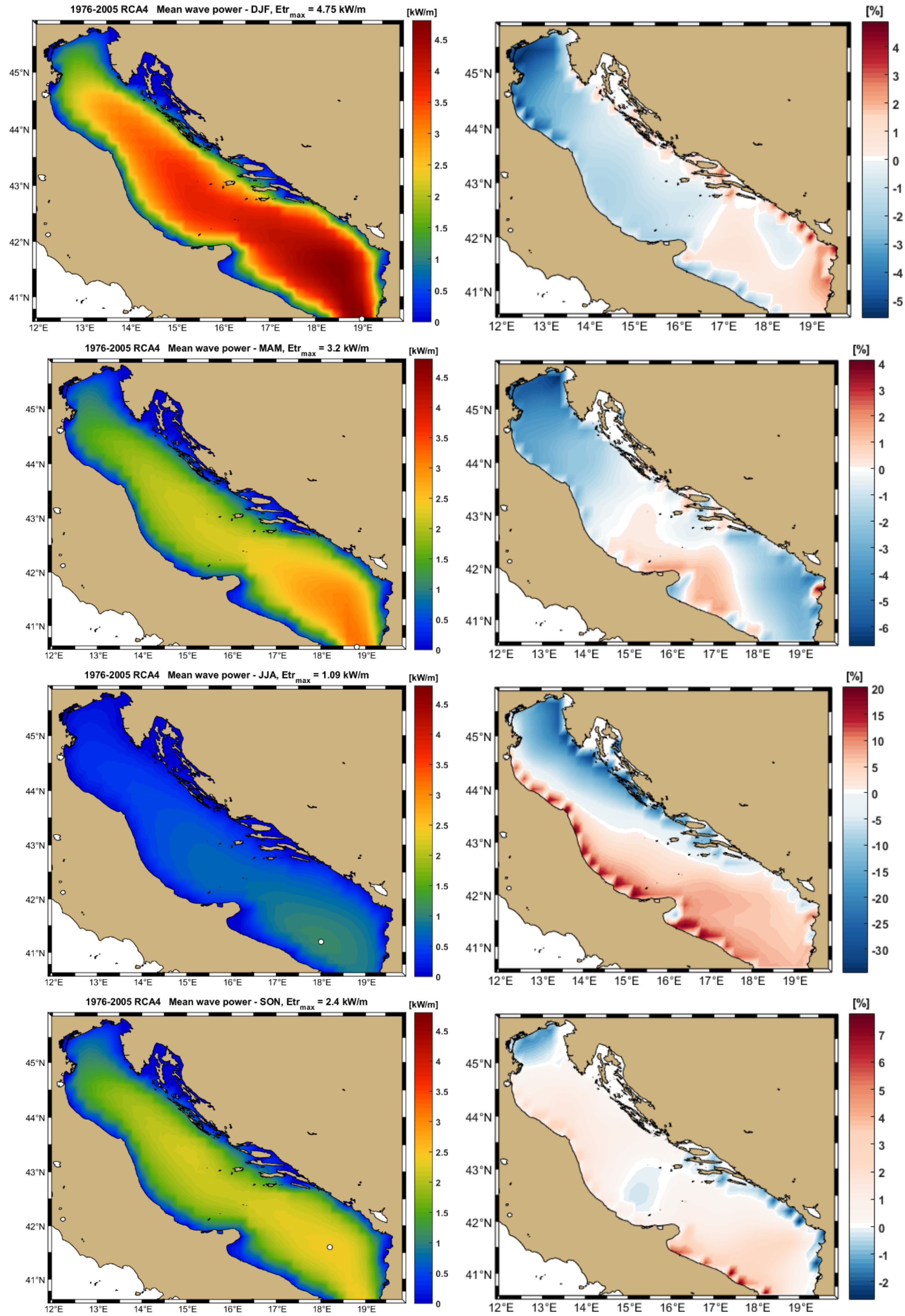


Figure 12. Seasonal average values of *Etr* for historical (1976-2005), results from SWAN forced with RCA4 wind fields – left panels; b) Seasonal changes in the mean *Etr* as a percentage relative to the historical period, for the near future under RCP4.5 – right panel

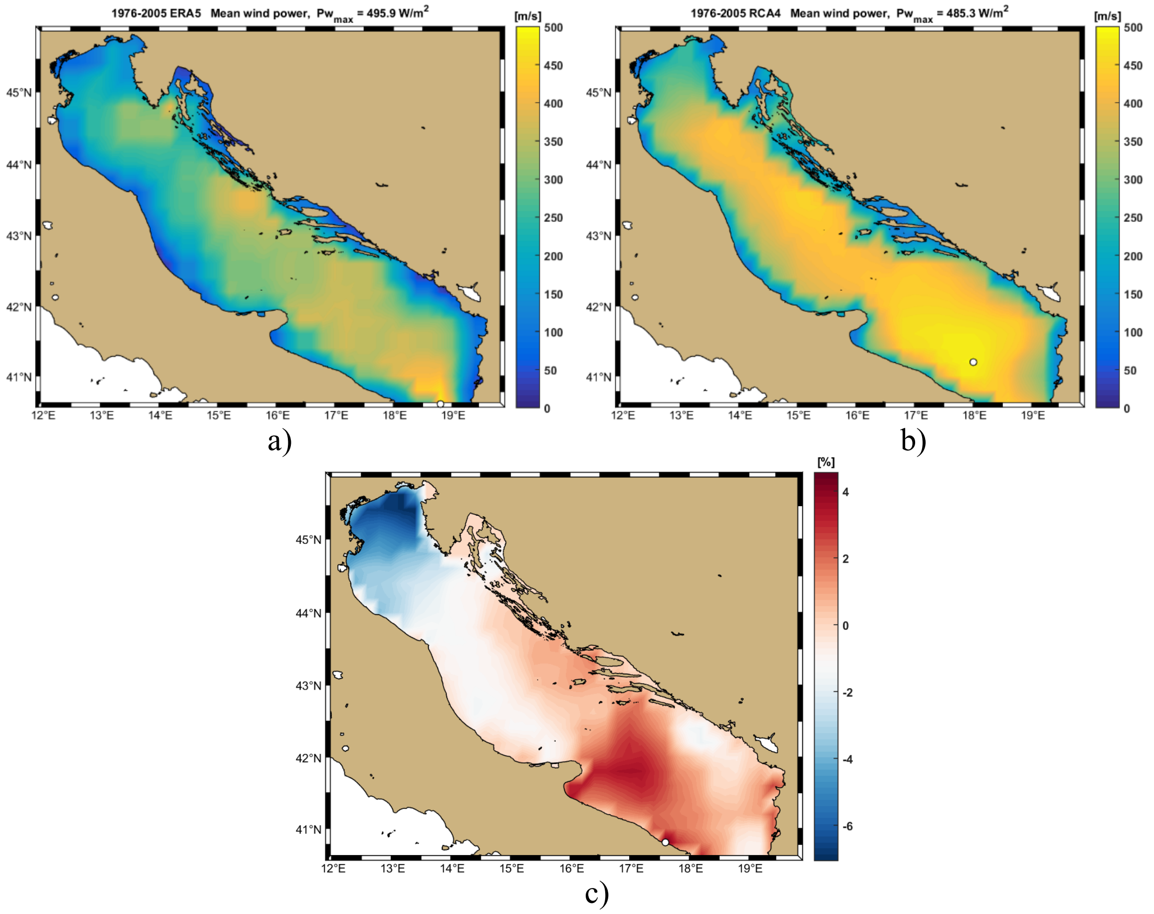


Figure 13. Average values of P_w for the recent past 1976-2005: a) P_w ERA5 fields; b) RCA4 P_w fields; c) normalized differences (*ND*) between the two P_w fields

The wind power density for the near future, computed based on U_{100} values, and its relative changes in comparison with the results from the RCA4 for the recent past are given in **Figure 14**. The images indicate an important increase of the wind power density almost all over the basin with *RC* values reaching 40% over extended zones.

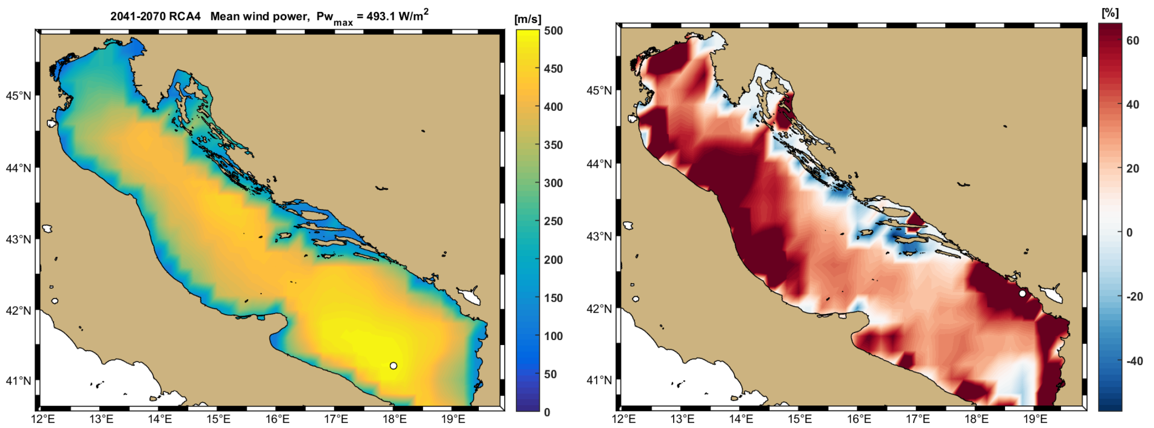


Figure 14. a) Average values of P_w for the near future 2041-2070; b) Changes of the mean P_w as a percentage relative to the recent past period for the near future corresponding to the RCP4.5 scenario

CONCLUSIONS

In the present study, the assessment of the environmental matrix (wind and wave) in the Adriatic Sea and its expected dynamics for the near future is carried out. The climate change impact on both components of the environmental matrix is made using results from two-time intervals, each covering a 30-year time slice. The first one (1976-2005) represents the recent past and is considered the reference period. The second comprises the near future (2041-2070, and the projections are made under the RCP4.5 emission scenario.

The comparison between the wind speed from ERA5, a widely used and reliable reanalysis database, and the wind speed produced by an RCM for the historical period, namely RCA4, indicates that there are no discrepancies between these data. So, the data provided by RCA4 can be used with confidence to study the near future expected dynamics of renewable resources.

Regarding the wave climate, a decrease of about 4.8% in terms of *Hs* means is expected for the near future in the north-eastern part of the Adriatic Sea, while in the south-eastern side of the sea, the decreases range from 0.5 to 2%. The central part of the basin seems not to be affected by climate change. The expected *RC* for the wind speed at 100 m over the sea level shows small variations over the Adriatic Sea, ranging from -3.8% to 2.2%, with positive values in the southern part of the basin.

The dynamics of the wave energy under RCP4.5 evaluated based on *RC* values indicates a reduction in the northwest part by up to 8%, while in the south-eastern part, an enhancement of the wave power of up to 10% is expected over extended areas. Autumn seems to be the season when in most of the basin, wave power increases of up to 8% are expected. An important enhancement of the wind power density is expected for the near future, with relative changes reaching 40% over extended geographical areas.

Finally, it must be highlighted that this work is only the beginning of more detailed studies about the evolution of the environmental matrix in the Adriatic Sea. An analysis of various points identified as having a high potential will bring probably more useful information. Furthermore, an analysis of various points identified as having a high potential will bring more useful information. ore wind data and wave model simulation results will be analysed to get a broader view of the aspects analysed here.

ACKNOWLEDGEMENT

This work was carried out in the framework of the research project CLIMEWAR (CLimate change IMpact Evaluation on future WAve conditions at the Regional scale for the Black and Mediterranean seas marine system), supported by the Romanian Executive Agency for Higher Education, Research, Development, and Innovation Funding – UEFISCDI, grant number PN-III-P4-PCE-2021-0015.

ERA5 data used in this study have been obtained from the ECMWF data server, while the wind fields under RCP4.5 scenario are from the EURO-CORDEX data servers.

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Paper submitted: 07.11.2023
Paper revised: 03.12.2023
Paper accepted: 09.12.2023