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ANALYSIS OF EXTREME WIND AND WAVE CONDITIONS IN THE BLACK SEA, AS REFLECTED BY THE ALTIMETER MEASUREMENTS

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ABSTRACT

The main objective of this work is to assess the spatial and temporal distribution of extreme wind and wave conditions in the Black Sea. In order to perform the proposed analysis, the target area was divided into four distinct regions, which were associated with the main geographical directions. Based on altimeter data, processed from the AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) platform, the variations of the wave and wind offshore conditions were analyzed for the time interval September 2009-March 2016. Following a detailed evaluation of the time series, it was possible to identify some energetic peaks, which were further investigated by taking into account the spatial distribution of the marine conditions. Based on these results, it can be mentioned that the extreme conditions reported for the waves do not always match those corresponding to the wind conditions, while in terms of spatial distribution, there were noticed large storm event, which cover the entire basin. As concern the storm conditions reported by the satellite measurements, there may be observed the most significant extreme events, during which the maritime activities can be restricted.

Keywords: Black Sea, wind and waves, offshore, altimeter data, AVISO

1. INTRODUCTION

The Black Sea is one of the most dynamic regions in the world, being considered an important economical and geopolitical environment. It is well known for the ship routes which connect Europe to Asia, as well as for the meromitic conditions reported below the sea surfaces or for the Danube Delta biosphere reserve, which is located in the western part of the Basin [1-3]. As concerning the natural conditions, it can be mentioned that previous studies reported more consistent wind and wave characteristics in the western part of the sea, being possible for some places to report extreme events, such as in the case of the Danube River mouths [4-6] or in the north-eastern part of the sea, more precisely, close to the Novorossiysk region, where the Bora wind occurs [7]. In the offshore areas, the safety of a ship (and its crew) is directly related to the extreme conditions encountered along the navigation routes, which could report more consistent values during the more energetic winter time. Although the oceanic areas usually report such events, during which large ships may easily capsize, this scenario may be also encountered in the enclosed sea areas, such as the Black Sea, where the extreme events cannot be underestimated [8-9]. Maybe the most visible effects of the storm events coming from the offshore areas is observed around the beach sectors, which are constantly under the abrasive action of the waves, the intensity of the beach erosion being related to the level of the energy induced by the breaking waves in the surf area. This is the case of the Romanian coastal environment, which, throughout his geographical position, is subjected to short but intense storm events, which influence the balance between the accretion-erosion processes in a negative way [10, 11]. The assessment of the natural conditions from the marine environments is also in the line with the current research activities in Europe, which are trying to limit or, at least, to attenuate these effects on one side or, eventually, to extract this energy throughout various renewable energy projects [12, 13].

A particularity of the marine areas is that they cover large water surfaces, which are difficult to monitor with in situ instruments or research vessels, which are more suitable for the shallow water areas. During the recent years, the satellite measurements and datasets coming from numerical models are starting to emerge, being already considered a high quality data sources, capable to provide an accurate picture of marine conditions, both in time and space. Each source of data is characterized by errors or gaps in the time series. For example, the in situ buoy may be affected by the extreme storm events, during which it will provide less accurate information. Regarding the altimeter missions, since they are travelling around the earth on a well establish orbits, it is possible that close to the shoreline (interface water-land) to report missing data. This is due to the fact that the high frequency signals sent by the satellites from an altitude of almost 1400 km, will be received back with ambiguous information, which, during the processing stage, could be removed since they will have a low quality.

Motivated by these aspects, the purpose of the present work is to assess the extreme events from the Black Sea throughout the altimeter measurements, which are coming from a multi-missions project maintained by AVISO.

2. METHODS AND MATERIALS

The map of the Black Sea is presented in Fig. 1.

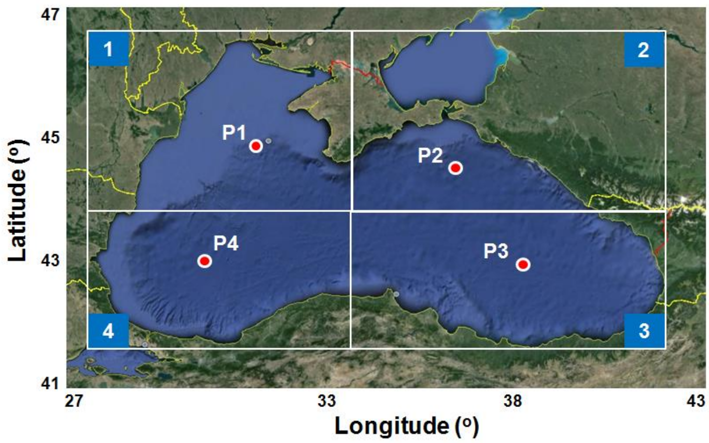

Fig. 1: General view of the Black Sea region. The reference sectors are denoted from 1 to 4, while the associated reference points were indicated with P1, P2, P3 and P4, respectively.

For this study, the entire area was divided into four sectors (1, 2, 3 and 4), for which the wind and wave conditions will be assessed. As a first step, the evolution in time of the two parameters considering the reference points will be identified: P1 (north-west), P2 (north-east), P3 (south-west) and P4 (south-east), respectively. In order to provide a general overview of the marine conditions, the reference points were defined in the offshore areas corresponding to deep water regions, being defined by the following coordinates: P1 - 44^o 5` N; 31 $^o$3` E; P2 - 44^o 5` N; 36$^o$ 6` E; P3 - 42^o 7` N; 38$^o$ 5` E and P4 - 43^{o}1` N ; 30$^o$ 1` E.

The spatial and temporal distribution of the considered parameters will be identified throughout the AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) measurements, which are obtained throughout a multi-mission process. In this way, information coming from multiple altimeter missions is used to obtain a high spatial resolution available on a global scale. More details regarding this project and the methods used to process the wind and waves parameters can be found in the documentation of the AVISO project [14].

For the present work, the measurements were processed for the time interval September 2009-March 2016, the dataset being defined by one measurement per day. Also, it is important to mention that the wind speed (denoted with *U10*) is reported at a 10 m height above the sea level, while the wave heights are indicated throughout the significant wave height parameter (*Hs*), which corresponds to the mean wave height (trough to crest) of the highest third of the waves. Usually, the *U10* parameter is considered for the meteorological applications while, for the renewable projects, this will need to be adjusted throughout a logarithmic law to the hub of a conventional wind turbine (80 meters). Since we consider the *Hs* values, it is possible to underestimate the real sea state, especially in the case of the extreme values, which play an important role for the seakeeping study of a ship.

In order to establish a common framework used in most of maritime activities, the Beaufort scale was considered to assess the intensity of the wind and wave conditions, accordingly. More details regarding the most encountered conditions corresponding to the Beaufort scale in the Black Sea are presented in Table 1.

Table 1. Beaufort scale for the *U10* and *Hs* parameters, respectively

Beaufort scale		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Details	**wind**	calm	smoke drift	wind felt	wind leaves	dust raised	trees begin to sway	large branches in motion	whole trees in motion
	sea	flat	ripples	small wavelets	large wavelets	small waves	moderate waves	long waves formation	sea heaps up
U10 (m/s)		<0.3	0.3-1.5	1.6-3.3	3.4-5.5	5.5-7.9	8-10.7	10.8-13.8	13.9-17.1
Hs (m)		0	0-0.2	0.2-0.5	0.5-1	1-2	2-3	3-4	4-5.5

3. RESULTS AND DISCUSSION

In Figure 2, the distribution of the wind and wave conditions for the point P1 is presented, which is located in the north-western part of the sea. Following the time series of the *U10* parameter, it can be observed that most of the values are located in the range of 2-4 m/s, with the mention that, for the interval 2015-2016, the wind conditions seem to be more consistent. In terms of the Beaufort scale, it can be observed that the classes 2 and 3 are dominant, which indicates a moderate wind climate. Nevertheless, from the time series, it can be also observed that the wind peaks can easily exceed 12 m/s, reaching, in some cases, a maximum of 16 m/s. Going to the *Hs* parameter (Fig. 2b), it can be observed that most of the waves are located below 2.5 m, being also noticed a peak of 5 m. Although the existence of these extreme values, most of the values are included in class 3, which is associated to the interval 0.5-1 m.

A similar distribution is presented in Fig. 3, this time considering the point P2.

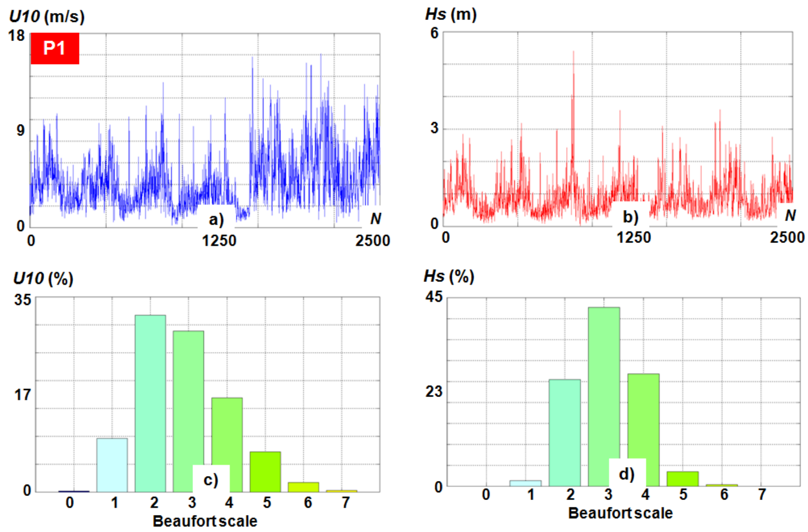

Fig. 2. Distribution of the wind and wave conditions, reported by the AVISO measurements for the point P1, considering the time interval September 2009-March 2016, where: a) *U10* - time series; b) *Hs* - time series; c) and d) Beaufort distribution for the *U10* and *Hs* parameters, respectively

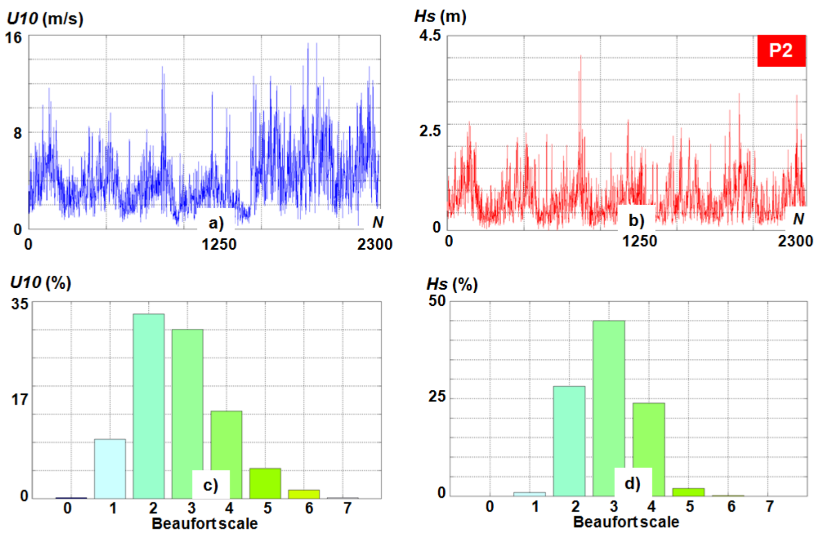

Fig. 3. Distribution of the wind and wave conditions reported by the AVISO measurements for the point P2, considering the time interval September 2009-March 2016, where: a) *U10* - time series; b) *Hs* - time series; c) and d) Beaufort distribution for the *U10* and *Hs* parameters, respectively

In general, the distribution of *U10* and *Hs* parameters is similar to those reported for the point P1, with the mention that, for this area, there are noticed lower values. In the case of the wind conditions, it can be mentioned a mean value of 4.05 m/s, while a maximum of 15.35 m/s is accounted in the winter season (October-March interval). For this time interval, the *Hs* heights report a mean value of 0.8 m, as compared to 4.05 m, which may be considered an extreme value.

Going to south-eastern part of the sea, the point P3 reveals the evolution of the two marine parameters. Regarding the *U10* values, it can be observed a constant distribution of the values, which are divided between winter and summer time, while for the *Hs* values can be highlighted the interval 2015-2016, which present more important values. Regarding the Beaufort scale, the values from the class 6 are more visible for the *U10* parameter, while most of the values of the wind and waves values are accounted by the classes 2 and 3.

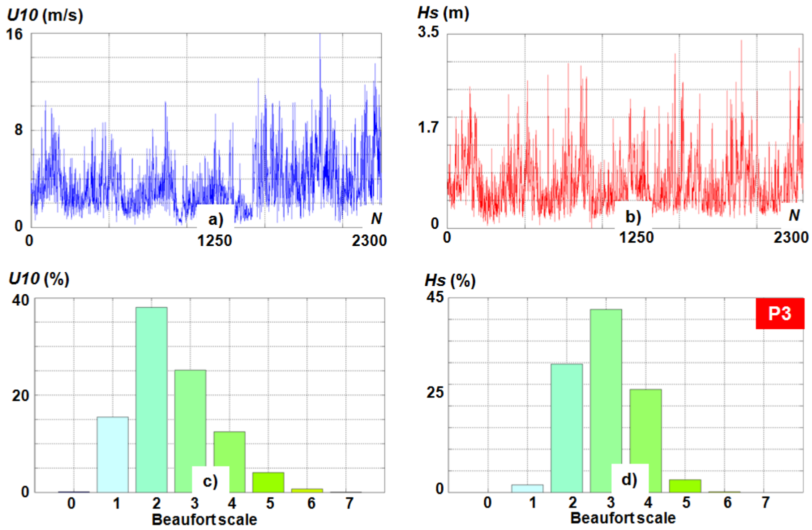

Fig. 4. Distribution of the wind and wave conditions reported by the AVISO measurements for the point P3, considering the time interval September 2009-March 2016, where: a) *U10* - time series; b) *Hs* - time series; c) and d) Beaufort distribution for the *U10* and *Hs* parameters, respectively

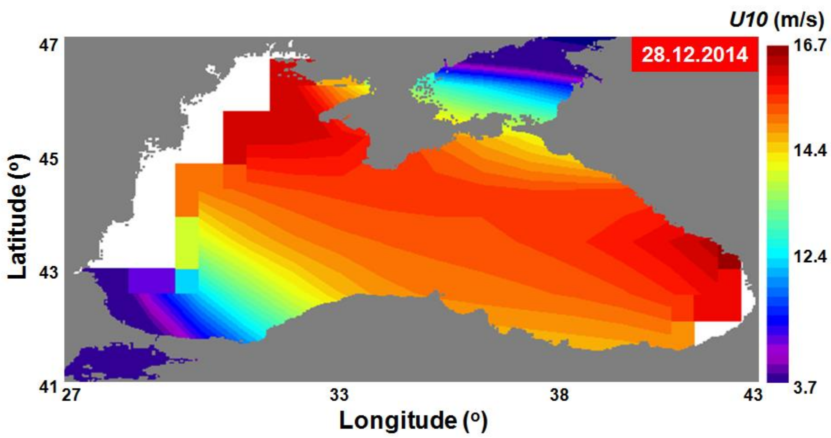

Fig. 5. Extreme conditions registered by the *U10* parameter, for the time frame 28.12.2014

Following the extreme values noticed in the time series of the points P1, P2 and P3, it was possible to identify a common maximum energy peak for the *U10* parameter, which occurs at the time frame 28.12.2014. This is presented in Fig. 5, for the entire sea basin, and, as it may be observed, it is the case of a massive storm, which covers the entire part of the Black Sea, whith the exception of the south-western part of the basin. For this time frame, there are reported missing data, especially in the western part of the sea, close to Romania, Bulgaria and Ukraine.

Figure 6 presents a similar analysis for the point P4 (south-west), while Figure 7 revealed an energetic conditions (for *U10*), which may be encountered in this part of the basin. As it can be observed, the time occurrence of this event is slightly different as compared to the points P1-P3, being shifted more to the north-western part of the Black Sea.

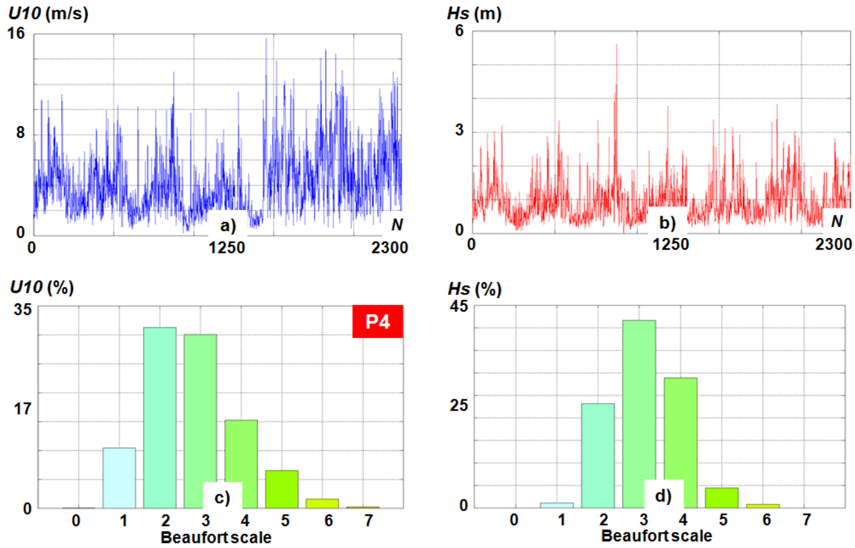

Fig. 6. Distribution of the wind and wave conditions reported by the AVISO measurements for the point P4, considering the time interval September 2009-March 2016, where: a) *U10* - time series; b) *Hs* - time series; c) and d) Beaufort distribution for the *U10* and *Hs* parameter, respectively

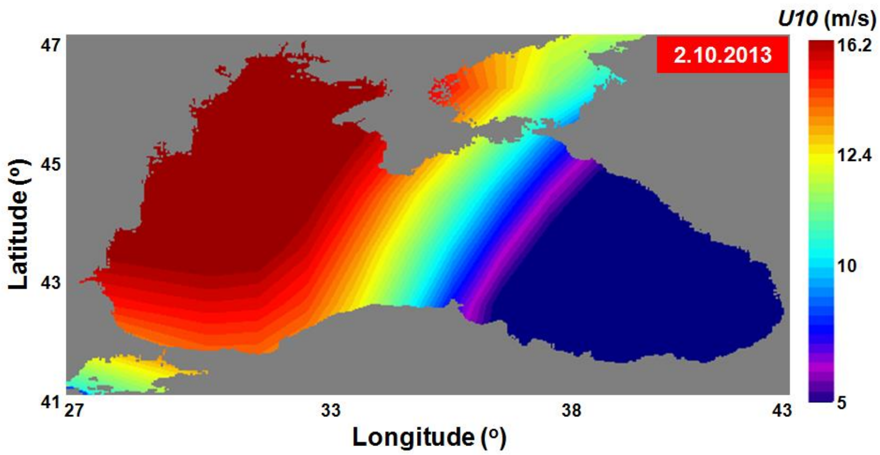

Fig. 7. Extreme conditions registered by the *U10* parameter for the time frame 2.10.2013

Going from wind to waves, Figure 8 presents an extreme condition reported by the points P1, P2 and P4, during the winter time. It can be observed that more consistent values are reported in the western part of the sea, which may reach almost 5.6 m, as compared to the extremity of the south-eastern sector, where the values gradually decrease until 1.4 m. In this figure, the conditions reported in the Sea of Azov (north) and Sea of Marmara (south-west) can be also observed. Figure 9 presents an extreme event (in terms of the *Hs* parameter), which is typically encountered in the southern part of the sea. This case corresponds to the time frame 8.01.2015. In the case of the point P3, the maximum values may reach a value of 3.4 m, while the mean values are located close to 0.8 m. In this case, the storm event seems to be generated in the south-western part of the sea, gradually extending to the central area.

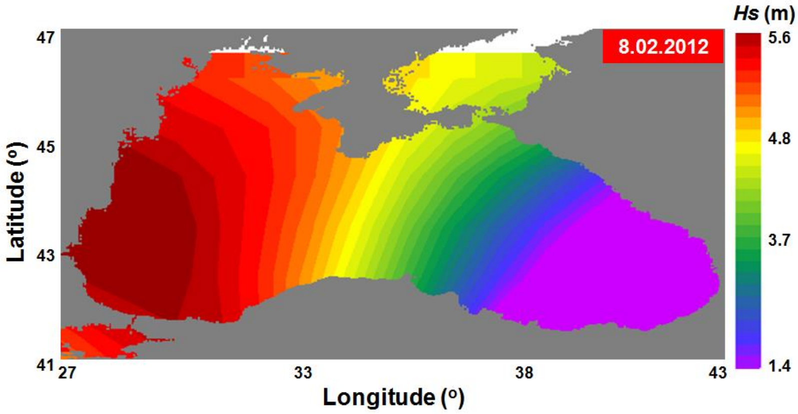

Fig. 8. Extreme conditions registered by the *Hs* parameter; values reported for the time frame 8.02.2012

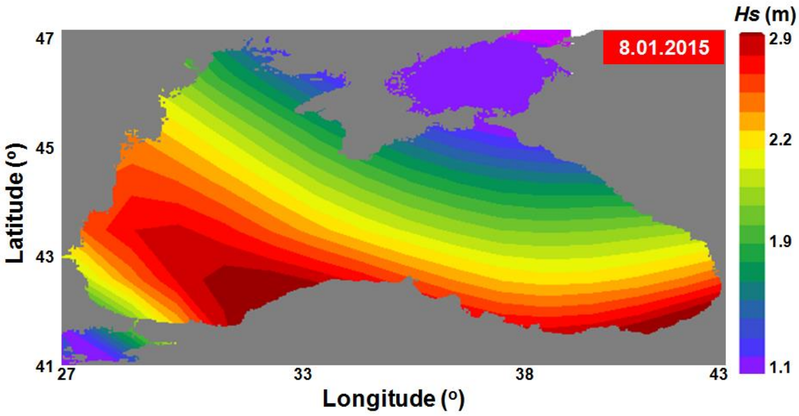

Fig. 8. Extreme conditions registered by the *Hs* parameter; values reported for the time frame 8.01.2015

4. CONCLUSIONS

In this paper, it was carried out a general assessment of the wind and wave conditions in the Black Sea, a special attention being paid to the extreme events that may be encountered in this geographical space. The analysis was based on the satellite measurements coming from the AVISO platform, the available datasets being processed for the time interval September 2009 - March 2016. From the analysis of the time series of the two most relevant parameters, wind speed and significant wave height, corresponding to the points P1-P4, it was possible to notice more consistent values during the recent years (2015-2016). In general, the values corresponding to the Beaufort scale are located in the classes 2 and 3, regardless of the reference point, with the mention that the point P1 seems to be located in a more energetic area. As concerning the storm conditions, it was highlighted the fact that the extreme events usually cover large areas in the Black Sea, with the mention that the south-western part of the sea seems to have the most important wave resources, while the most significant wind conditions appear to be in the north-western side of the sea. The results presented in this work can be considered interesting since they reveal that extreme conditions are equally distributed between the offshore and nearshore areas, more consistent values being registered in the western part of the sea, which also includes some major shipping routes, in this side being located also the southern gate in the seventh Pan European transportation corridor, which is the Danube-Maine-Rhine inland navigation system.

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