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Wind waves on the Black Sea: results of a hindcast study

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Abstract

In this study we describe the wind waves fields on the Black Sea. The general aims of the work were the estimation of statistical wave parameters and the assessment of interannual and seasonal storm variability. The domain of this study was the entire Black Sea. Wave parameters were calculated by means of the SWAN wave model on a 5 km × 5 km rectangular grid. Initial conditions (wind speed and direction) for the period between 1948 and 2010 were derived from the NCEP/NCAR reanalysis. In our calculations the average significant wave height on the Black Sea does not exceed 0.7 m. Areas of most significant storminess are the south-western and the north-eastern corners as expressed in the spatial distribution of wave heights, wave lengths and periods. Besides that, long-term annual variations of storminess were estimated. Thus, linear trends of the annual total duration of storms and of their quantity are nearly stable over the reanalysis period. However, an intensification of storm activity is observed in the 1960s–1970s.

1 Introduction

Any human activity in the marine or coastal areas is directly affected by the ocean. To settle, live, work and plan in these areas requires data on the climate of these seas. As the oceans and their shores are used more and more intense for very different purposes, such as marine transports and offshore mining operations on one hand and recreation on the other, this data has to meet more and more exacting requirements. It must be as reliable and accurate as possible. A regular distribution in time and space is a great advantage of any dataset, as it makes it more convenient to use for further purposes.

Nowadays numerical modelling seems to be the most attractive method of generating such datasets. The main advantage of this technique is its flexibility relative to the formulation of initial conditions, the calculated parameters and the resolutions –

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both temporal and spatial. Another preference of modelling studies is the possibility to perform hindcast and forecast calculations using archived or forecasted wind fields. Operative wave forecast on different spatial scales is a state-of-the-art domain where numerical modelling is used.

Traditional in situ measurements do not possess these advantages, as they are usually performed during relatively short survey campaigns and/or by means of gauges at locations that do not permit to obtain data located over the whole basin of interest. However, such measurements are very important as they are the only way to validate and calibrate the models.

Much attention was paid to the studies of the oceans' wave climate and its recent variability. This research is carried out on a variety of both temporal and spatial scales. Thus, a part of them is dedicated to global wind and waves studies (Peterson and Hase, 1987; Sterl et al., 1998). However, more or less regional studies prevail in this domain, e.g. studies of the Northern Atlantic Ocean and European Seas. In order to obtain data on wind and waves being regularly distributed in time and space in this domain several hindcast studies were performed (Kaas, 1996; Soares, 2002). A relationship between the North Atlantic Oscillation (NAO) and alterations in the wave climate and was determined (Kushnir, 1997). Finally, studies of wave regimes are also carried out on scales much smaller than seas, such as gulfs and bays (e.g. Soomere, 2005).

Offshore and coastal storms are the most hazardous combined action of wind and waves. They may cause severe damages both offshore and on land (Alexander et al., 2005; Matulla, 2008). Marine storms are subject of many studies. For example, a statistical assessment of storms off the Eastern coast of the USA during more than 40 yr is presented in (Dolan, 1988). The changes in storm activity during the last decades is much discussed. Thus, no significant storminess change is observed in the German Bight since 1876 (Schmidt, 1993). On the other hand, a 40 yr wave hindcast carried out for the whole Northern Hemisphere indicated a rise of significant wave height in the Northeast Atlantic (Wang and Swail, 2001). This phenomenon is seen to have a relation

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terations of wave parameters and even their statistical distribution properties are stated as a result of wave impact. A demonstration of the implementation of numerical models for the simulation and forecast of oil spill propagation during offshore accidents in this region can be found in L. Rusu (2010). Furthermore, a detailed description of the multiannual trends in the storm parameters over the western part of the Black Sea shelf is given in Valchev et al. (2012).

The energetic potential of wind waves in coastal water areas was highly appreciated during the last several decades. Regarding the Black Sea, the problem of predicting and assessing the energetic potential of waves is discussed in Rusu (2009) and Akpinar and Kömürcü (2012). The first paper is focused on the western part of the sea, whereas the south-eastern coastal areas are studied in the latter.

The present paper describes some preliminary results of a modelling study of wave parameters and their alterations on the Black Sea during more than 60 yr basing on the NCEP/NCAR reanalysis data (Kalnay et al., 1996). This reanalysis was not used for the assessment of wind waves parameters on the entire Black Sea previously. Our work had two general goals. First, we attempted to obtain modern climatic parameters of wind waves on the Black Sea. Second, the interannual and multidecadal variability of storm waves was assessed.

3 Study area, data and methods

3.1 Study area

The domain of the presented study is the entire Black Sea. The Black Sea is a semi-enclosed basin of the World Ocean located between 41° and 46° N and 27° and 42° E. It is connected to the Mediterranean Sea through the Sea of Marmara and the Bosphorus and Dardanelles Straits in its south-western part and to the Sea of Azov through the Kerch Strait in the opposite north-eastern one. Another feature of the Black Sea is its steep continental slope and very narrow – except of the western and south-western

coastal areas – continental shelf. Thus, the greater part of the sea is a basin with a relatively flat bottom relief and depths exceeding 2000 m. An expanded description of the whole Black Sea system can be found in (Özsoy and Ünlüata, 1997) and (Kostianoy and Kosarev, 2005).

5 The atmospheric circulation in the region is influenced by the configuration of the Azores and Siberian high pressure areas and the Asian low pressure area. Thus, in winter northeastern winds with speeds of 7–8 ms⁻¹ prevail. Eastern winds with speeds of 5–7 ms⁻¹ are predominant only in the southeastern areas of the sea. On the other hand, northwestern winds prevail in summer with typical speeds of 2–5 ms⁻¹ in coastal areas and 3–5 ms⁻¹ offshore. Wind speeds decrease in general from west to east (Dobrovolskij and Zalogin, 1982).

10 Besides this, local (mesoscale) winds, such as breezes, mountain-valley circulation, slope winds, foehns and bora have a remarkable impact on the atmospheric circulation pattern in the coastal areas of the Black Sea. The speed of breezes varies between 1–3 ms⁻¹ for onshore and 3–5 ms⁻¹ for offshore ones. Bora events are much more expressed with wind speeds reaching 25–30 ms⁻¹ on the coast (Kostianoy and Kosarev, 2005).

3.2 Data

20 The data used in this study may be divided into two general groups: data on the bathymetry and coasts of the Black Sea and wind data in the studied domain.

An accurate dataset on the bathymetry is needed to create the digital model of the bottom topography and the numerical grid for further calculations. In order to obtain such a dataset a hydrographic chart of the Black Sea issued by the Main Naval and Oceanographic Administration of the Russian Ministry of Defense in 1996 was used. 25 The scale of this chart is 1 : 2 500 000. Isobaths corresponding to depths of 20, 50, 100, 200, 500, 1500 and 2000 m are plotted on the chart as well as 514 separate points with corresponding depth values.

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The scanned image of this map was processed by means of the Golden Software MapViewer package. This package was used to digitize the chart. As a result, a database containing geographic coordinates of points and corresponding depth values was created. Afterwards geographic coordinates of all collected points were transformed to Cartesian ones and the irregularly distributed depth values were interpolated onto the nodes of a rectangular grid with a spatial resolution of 5 km × 5 km. In order to avoid computational errors, small bays and capes having sizes roughly equal to the grid size were smoothed. Thus, a 129 × 242 cells matrix was created. This matrix was used as the computational grid in the study (Fig. 1). The same database was previously applied for numerical hydrodynamic studies of the Black Sea (Arkhipkin et al., 2013).

Continuous wind data is needed as forcing input for the calculation of the wave parameters. For this purposes wind speed series (decomposed to u and v components) at 10 m height above the sea surface were selected from the NCEP/NCAR reanalysis (Kalnay et al., 1996). This reanalysis contains hindcasted values of various meteorological parameters dating back to 1948. The temporal resolution of this dataset is 6 h, while the spatial one is 1.875° in the longitudinal direction and 1.9046° in the latitudinal one. Data corresponding to the study domain were selected and interpolated on our computational grid. This reanalysis was chosen first of all due to its enormous temporal extend, which is significant bigger than most other analogues. A validation of wind data at 10 m height from the NCEP/NCAR reanalysis against measurements performed at regularly meteorological stations and voluntarily on vessels in the investigated region is given in (Kovzova, 2006).

3.3 Wave model

Wave parameters were calculated by means of the third-generation spectral wave model SWAN (Booij et al., 1999; Ris et al., 1999). This model is widely used all over the world for the calculation of wave parameters on both oceanic and coastal scales, including the Black Sea (Akpinar et al., 2012). Version 40.81 of the model was applied. Calculations were carried out in third-generation mode. Exponential wave growth

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Two areas with most expressed storminess are determined in the Black Sea – the south-western and the north-eastern ones. Calculated wave heights exceed 6.5 m here (Fig. 3). Approximately the same areas are characterized by maximal wave lengths and periods exceeding 55 m and 7 s respectively. This is similar to values presented in e.g. (Kovzova, 2006), but differs from these mentioned in (Polonsky et al., 2011). Thus, maximal values of wave heights in the southwestern parts of the sea reported in the latter paper are nearly twice as high as according to our results.

On the other hand, the calmest areas of the sea are its south-eastern and north-western parts. The first one is not strongly affected by the impact of cyclones, whereas the second one is the only area in the Black Sea with a clearly defined shelf. Thus, wave growth is limited by the action of bottom friction here. In general, maximal wave heights decrease towards the coasts similarly to the average heights. However, the north-eastern coast is periodically affected by storm waves higher than 6 m. A recent example of such an event is the storm that occurred in November 2007 (Bukhanovskij et al., 2009).

The spatial distribution of the storminess intensity can be explained by the position of the atmospheric circulation which is responsible for the wind pattern. There are two prevailing synoptic situation types causing storms over the Black Sea. The first type is characterized by the trough of atmospheric pressure spreading from the eastern Mediterranean towards the Black Sea and often forming a local cyclone over the Black Sea. Its further movement to the north is blocked by the vast high pressure centre over Eastern Europe (Fig. 6). Under the influence of the southern trough, northeasterly, easterly and southeasterly winds are predominant over the Black Sea (Fig. 7). When an independent Black Sea cyclone is generated at the periphery of the trough, the pattern of wind direction over the sea is more complicated and can be opposite in different parts of the sea. For the second type, it is also a cyclone over the Black Sea or nearby, but the large-scale configuration of the atmospheric pressure field differs from the first type. The appearance of the cyclone is accompanied by a quick propagation of a trough from Scandinavia and the Baltic Sea. At the same time, high atmospheric

pressure prevails over the Balkans (Fig. 8). Such a situation may lead to strong north-western, western and south-western winds (Fig. 9) (Surkova et al., 2013).

An estimation of wave heights possible once in 100 yr was performed using the logarithmically normal distribution and based on the dataset of calculated wave heights.

5 According to this assessment, waves higher than 14 m may occur in an offshore area surrounding the Crimean peninsula from the southwest, south and southeast (Fig. 10), which is similar to data given in (Kovzova, 2006).

4.2 Temporal variability of Black Sea storminess

Some preliminary results concerning the average storminess parameters on the Black Sea were derived during this work. The presence of waves higher than 2 m during several output time steps was considered as a storm event. In total, more than 1500 of such cases were observed. The average duration, space and track length of storms is identified. The storms have also been ranked depending on the maximal calculated wave height. The results of this analysis are presented in Table 1.

15 Another problem related to the study of storminess is the assessment of its temporal variability. During this project, we managed to achieve some results in this domain. First, the interannual variability of total storm duration (Fig. 11) and of the quantity (Fig. 12) of storms over the period from 1948 to 2010 was analyzed. The linear trends of these series show a negligible decrease of both annual duration and quantity of storms – -0.62 hr^{-1} and $-0.02 \text{ stormsyr}^{-1}$. At the same time it is possible to determine a period of relative active storminess in the Black Sea. This period begins in the early 1960s and ends approximately in the middle of the 1970s. Such results generally match the data on storminess trends at the western coast of the Black Sea described in (Valchev et al., 2012).

25 Finally, the seasonal distribution of storm events was assessed. The maximal value of total average storm duration corresponds to winter months, especially to January. However, most prolonged heavy storms with wave heights exceeding 5 m do not meet this rule and are observed in February. The calmest season of the year is summer.

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Cases of wave heights exceeding 4 m were found only in July, whereas storms with waves over 5 m high were not observed from April to September at all (Fig. 13).

5 Final considerations

This paper shows the results of a hindcast study of wind waves on the Black Sea based on a continuous numerical calculation for the period between 1948 and 2010. The enormous length of this period allows to obtain reliable statistical and extreme parameters of wind waves, as well as to assess the evolution of the Black Sea wave climate.

During this research average and extreme parameters of wind waves on the Black Sea were derived, which generally match with recently published results. Besides this, an assessment of interannual and seasonal variability of storms on the Black Sea was carried out. A slight negative trend of both annual duration and quantity of storms is observed.

The results reported in this paper can be explored in further researches with the use of other datasets and methods such as meteorological hindcasts having a smaller temporal and/or spatial resolution, unstructured numerical grids and coupled models permitting the calculation of both waves and hydrodynamic parameters. The latter is expected to be especially useful for studies of the characteristics in coastal areas, bays and straits.

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Table 1. Quantity and average duration, area and path length of storms.

H_S m	Quantity	Average duration, h	Average area, km ²	Average path length, km
$2 \leq h < 3$	1091	17.53	61 135	218
$3 \leq h < 4$	327	36.43	172 246	506
$4 \leq h < 5$	76	50.17	239 343	597
$h \geq 5$	19	68.68	259 047	672
Total	1513	23.90	96 568	305

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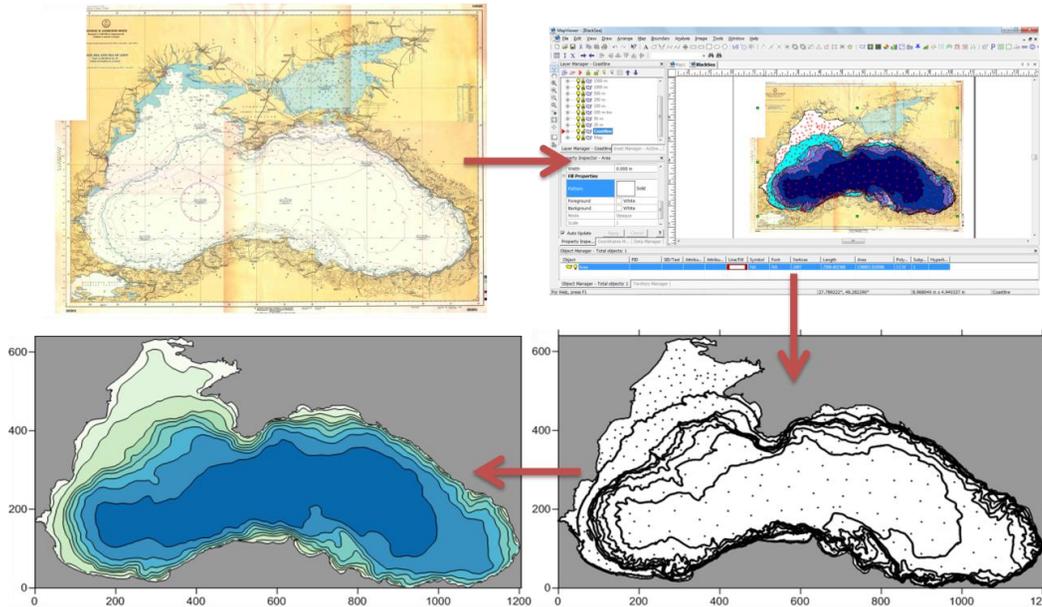


Fig. 1. The process of creating a rectangular matrix by digitizing a scanned map image.

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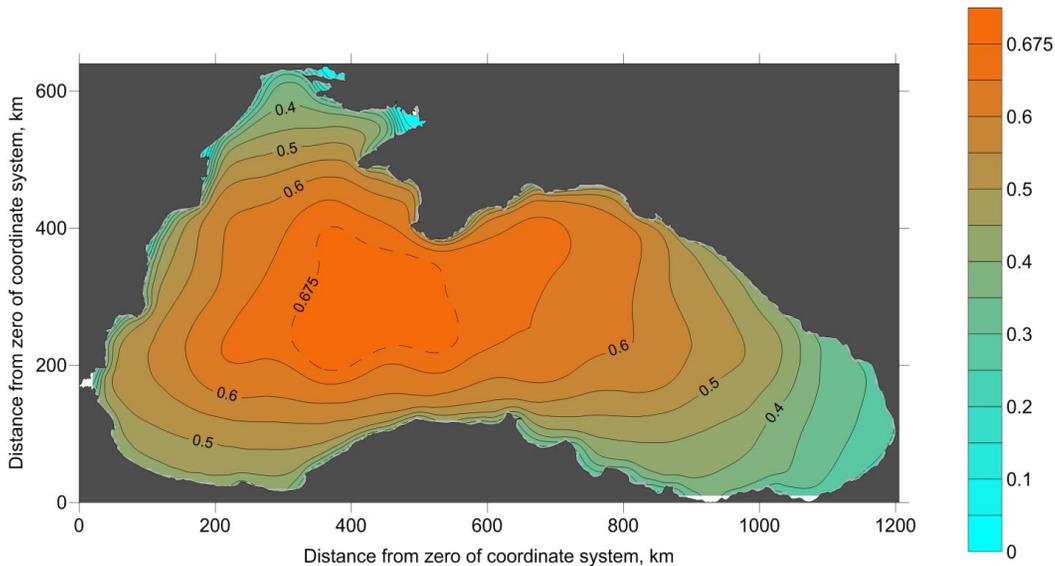


Fig. 2. Average calculated significant wave height, m.

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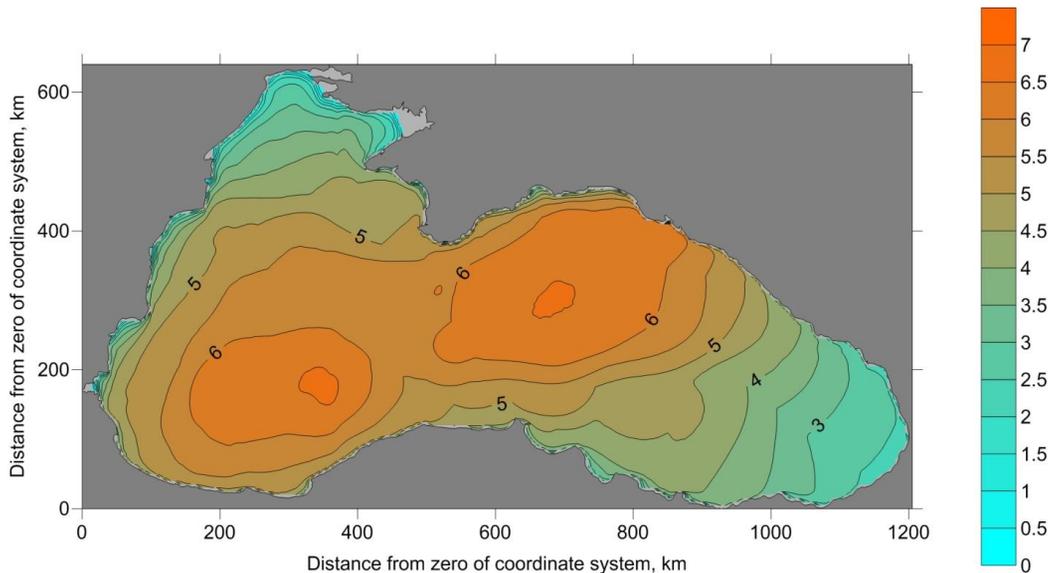


Fig. 3. Maximal calculated significant wave height, m.

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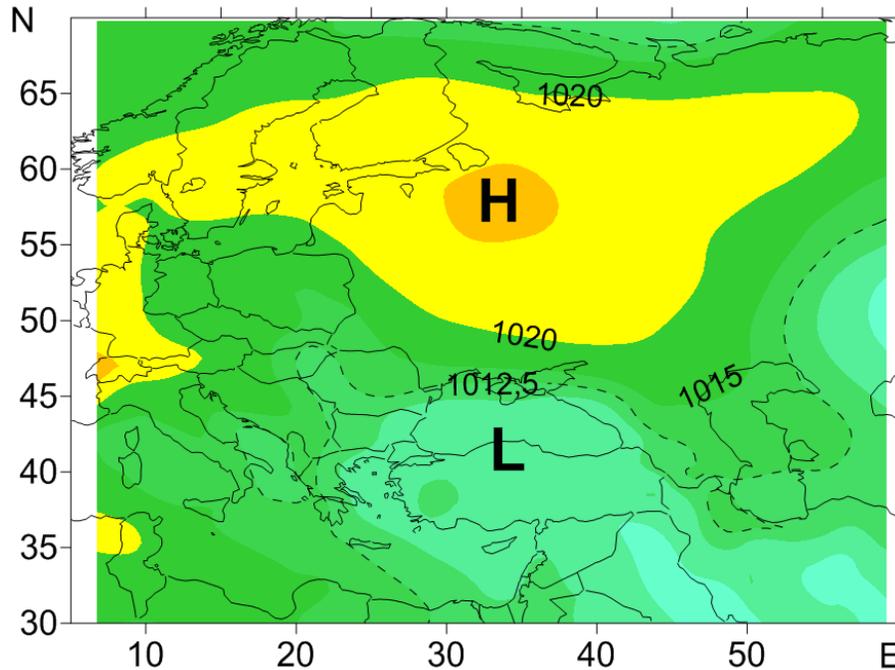


Fig. 4. Air pressure at sea level (hPa) showing a Mediterranean cyclone passing over the Black Sea (12 September 2003).

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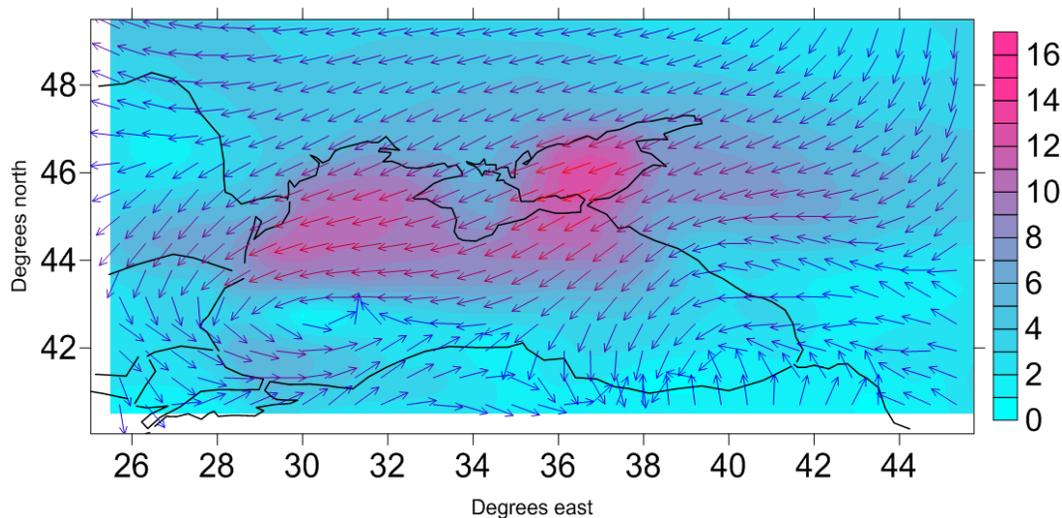


Fig. 5. Wind velocity (ms^{-1}) and direction corresponding to the pressure field shown by Fig. 4.

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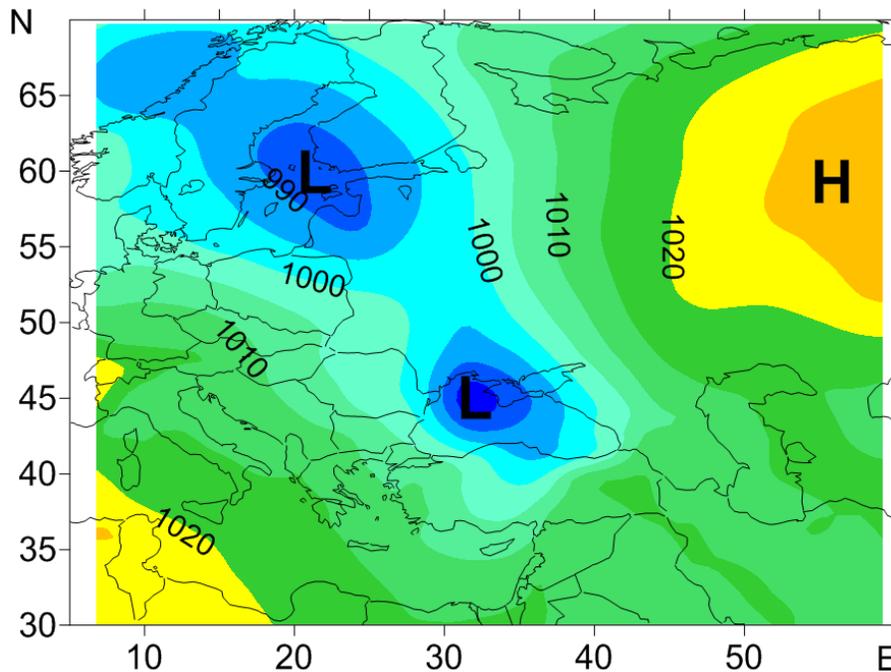


Fig. 6. Air pressure at sea level (hPa) showing the propagation of a cyclone from northern Europe towards the Black Sea (11 November 2011).

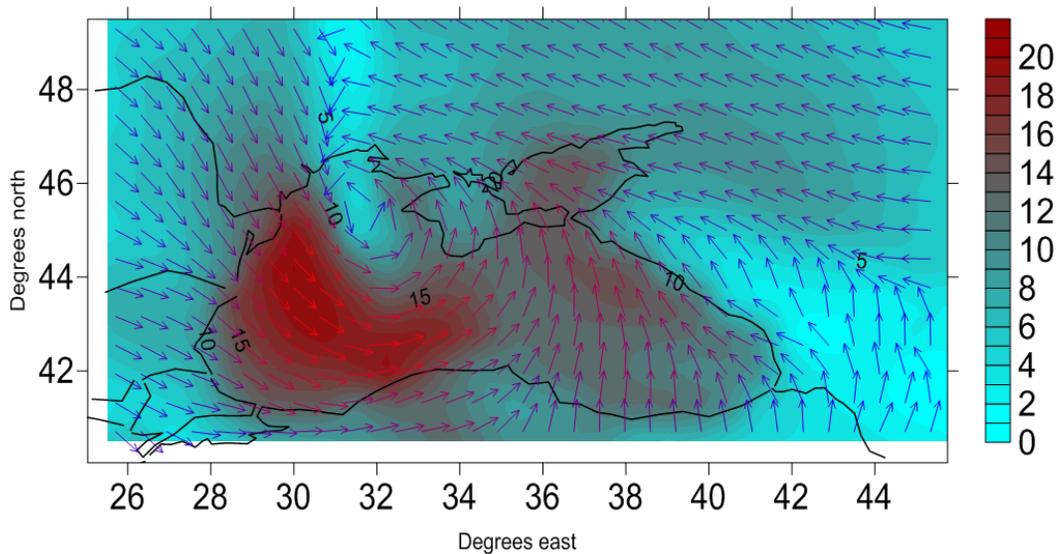


Fig. 7. Wind velocity (ms^{-1}) and direction corresponding to the pressure field shown by Fig. 6.

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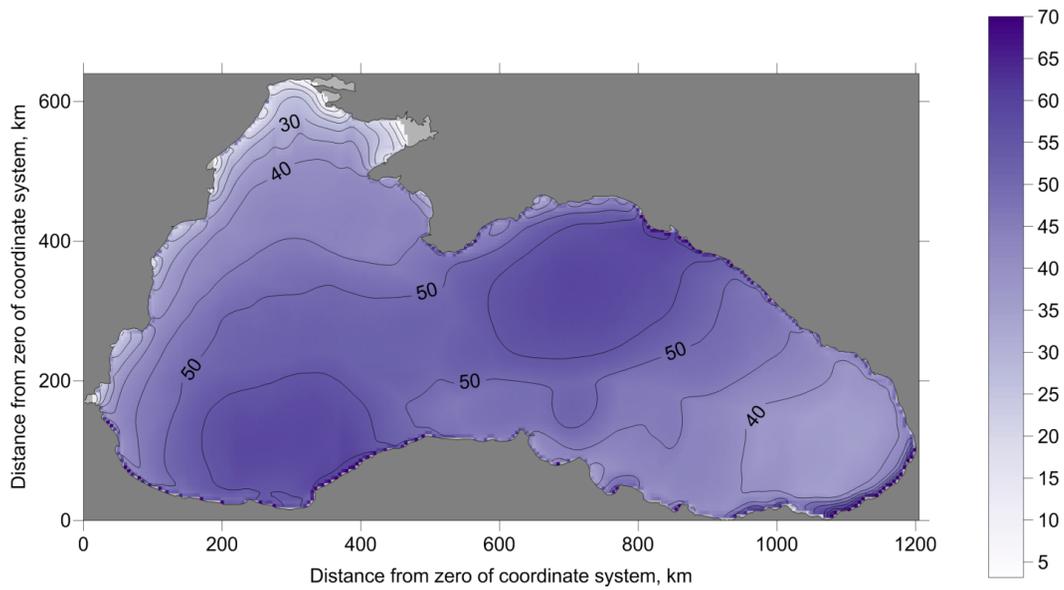


Fig. 8. Maximal calculated wave length, m.

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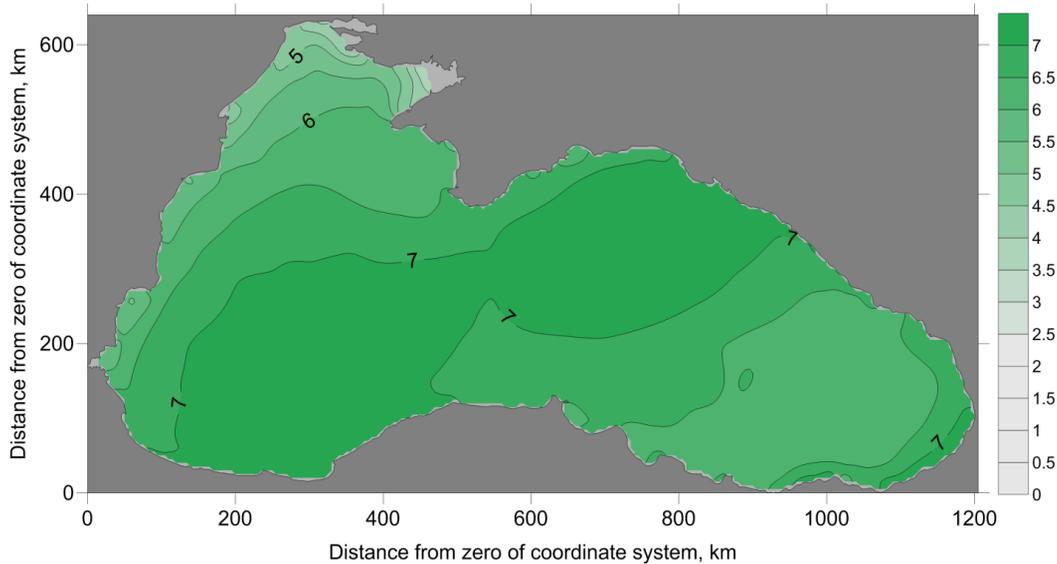


Fig. 9. Maximal calculated wave period, s.

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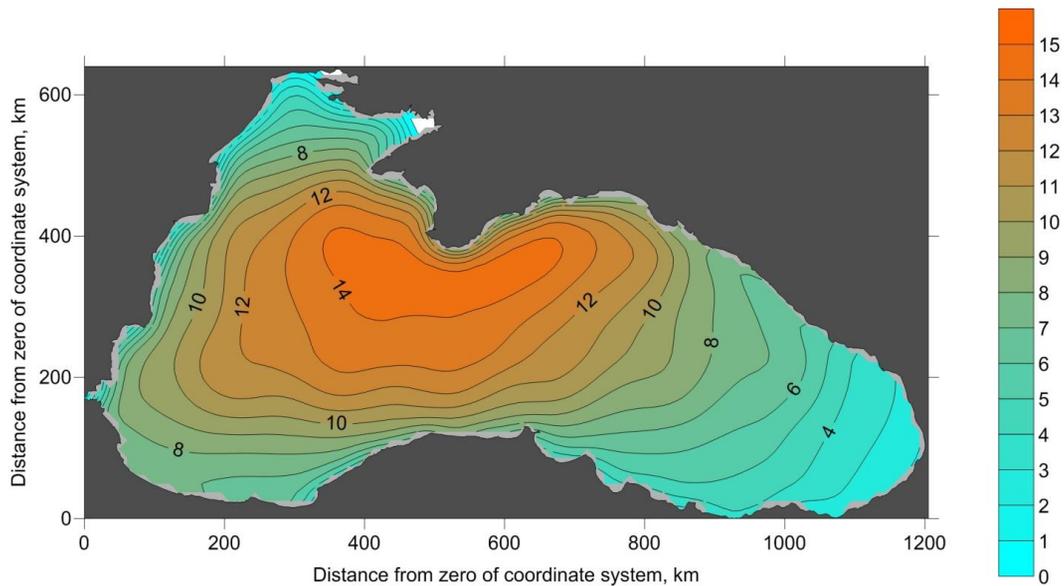


Fig. 10. Wave height of 100 yr repeatability, m.

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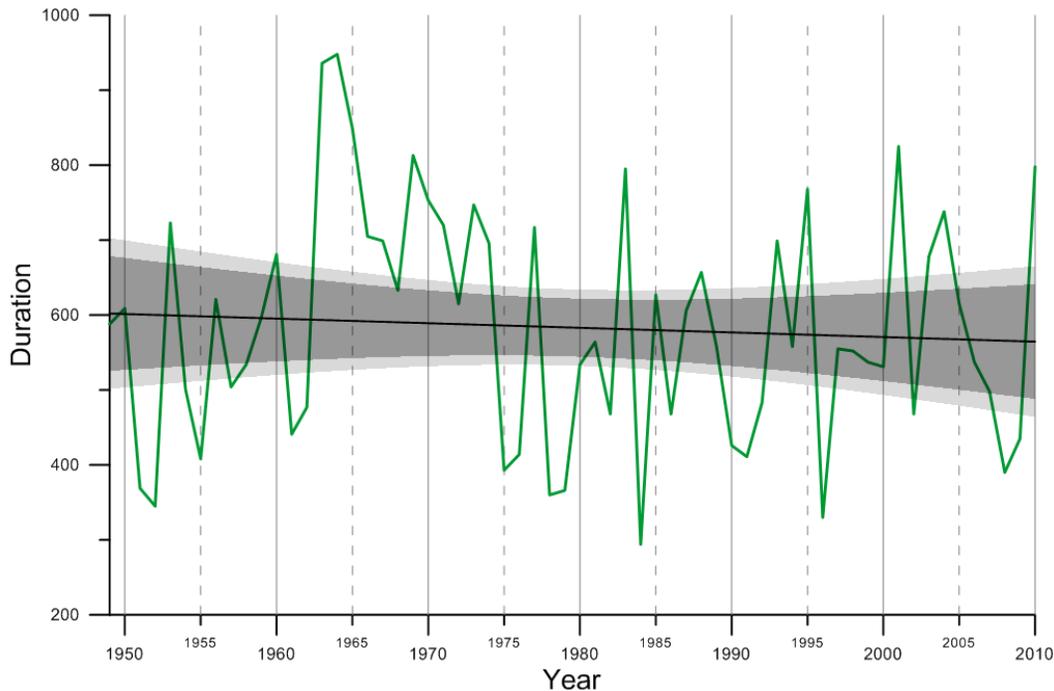


Fig. 11. Variability of total storm duration per year, h, its linear trend (-0.62 hr^{-1}), 95 % (dark grey) and 99 % (light grey) confidence intervals.

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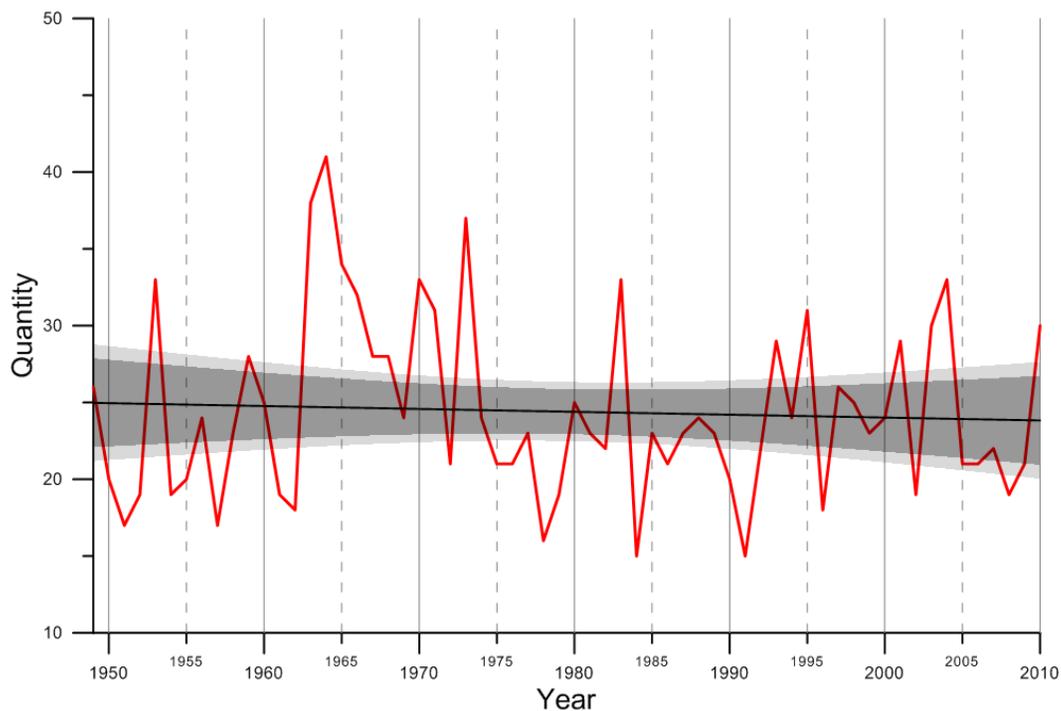


Fig. 12. Variability of storm events per year, its linear trend ($-0.02 \text{ storms yr}^{-1}$), 95 % (dark grey) and 99 % (light grey) confidence intervals.

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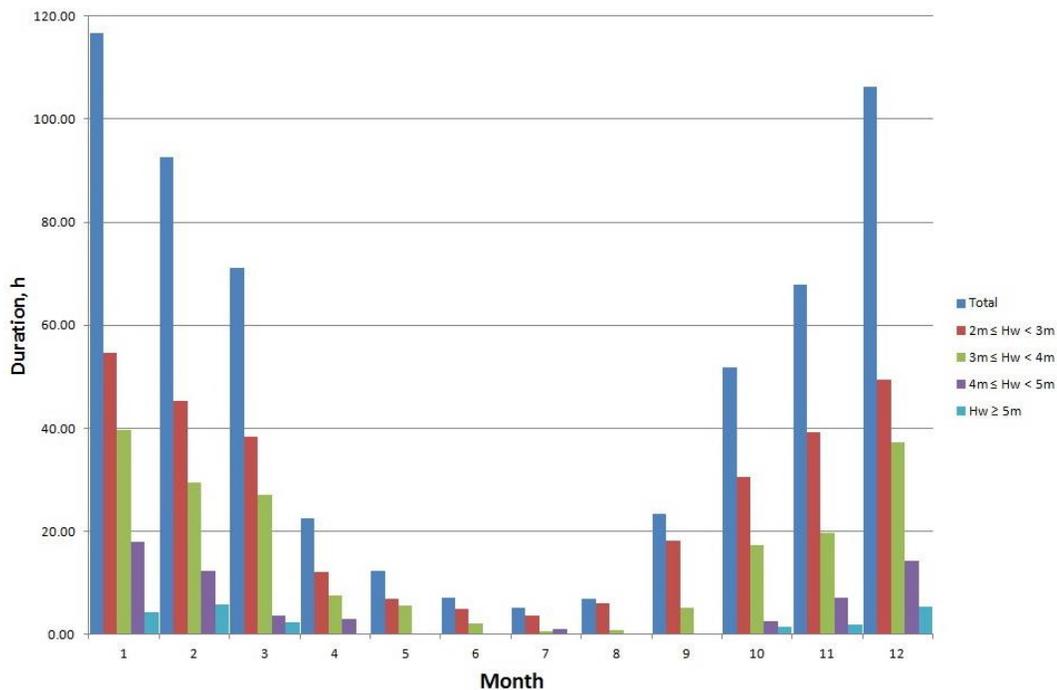


Fig. 13. Average duration of storms per month (total and wave height depending), h.

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