═══════ **OCEANOLOGY** ═══════

Extreme Wind Waves on the Northeastern Shelf of the Black Sea

B. V. Divinsky[a],* and Ya. V. Saprykina[a]
Presented by Academician M.V. Flint February 12, 2024

Abstract—The purpose of this work is to investigate extreme storm waves in the coastal zone from the village of Volna (the Kerch Strait area) to Adler on the northeastern shelf of the Black Sea over a climatic time span. The main method of research is numerical modeling using the MIKE 21 SW spectral wave model. As a result of calculations, hourly fields of spatial distributions of key wave parameters are obtained for the entire Black Sea water area from January 1979 to December 2023, i.e., for the past 45 years. The analysis is conducted with respect to the separation of the wave field into two components: pure wind waves and swell. Research has revealed that, over the past 45 years, the northeastern coast of the Black Sea was affected by 41 storms with significant wave heights exceeding 5 m. Two November storms in 2007 and 2023 are distinguished by their extreme characteristics. The significant heights of mixed waves during the storms reached 9 m, and the energies exceeded 500 kW/m. The average heights of mixed storm waves for the entire coast vary within 4–6 m, and the average energies are around 150 kW/m. The highest waves develop in the areas of Anapa, Utrish, and Idokopas. The average values of the heights and energies of pure wind waves have a common tendency to decrease from the northwestern coast to the southeastern, while for swell, on the contrary, they tend to increase. Several relatively homogeneous segments in terms of the developing wind waves and swell are identified in the coastal zone. In the structure of average storm waves between the village of Volna and Anapa, wind waves absolutely dominate. Between Cape Myskhako and Idokopas, the contribution of wind waves to the total wave power exceeds the swell by a factor of 2–2.5. Between Arkhipo-Osipovka and Tuapse, the power of pure wind waves slightly surpasses the power of swell. Further, south of Tuapse, the contribution of swell becomes predominant. Two regions are distinguished in terms of the ratio of the contribution of wind waves and swell along the coast: in the vicinity of Anapa, the overall wave climate is almost fully determined by wind waves, while in Adler, by swell.

Keywords: Black Sea, extreme storm, wind waves, swell, numerical modelling, wave climate

DOI: 10.1134/S1028334X24601676

INTRODUCTION

Surface wind waves are one of the determining factors for the safety of sea transport, the exploitation of shelf zones, and the development of coastal dynamic processes. Sea waves directly affect infrastructure, ecology, and the recreational potential of the coastline. The study of extreme waves that are intrinsically destructive is of greatest theoretical and practical interest.

Extremely dangerous storms can develop in the Black Sea under the influence of deep cyclones with significant wave heights, exceeding 12 m in the deep water [1–6]. The coastal zone is most strongly affected by the consequences of extreme storms. According to information from open sources, as a result of the November storm of 2023 in the northeastern part of the Black Sea, the coastal infrastructure was severely damaged, as a result of damage to railway tracks, destruction of embankments, berths, boat slips, residential buildings, and beach cafes. In the Adler region, eight out of 13 beaches were affected, 30 beaches in Anapa, and 69 in Gelendzhik. The restoration of the beach infrastructure in Sochi will cost more than 200 million rubles, and in Sevastopol, about 700 million rubles. The preliminary sum of total damage caused only to the regions in Crimea as a result of the natural disaster was almost 40 billion rubles.

The planning of economic activities and prevention of the consequences of natural hazards require information about the main parameters of storm waves in the coastal zone based on climatic data. Under con-

---
[a] *Shirshov Institute of Oceanology,*
Russian Academy of Sciences, Moscow, 117997 Russia
*e-mail: divin@ocean.ru

ditions of the almost complete absence of operating monitoring stations (we mean within the jurisdiction of Russia) that measure the characteristics of sea waves, mathematical modeling is the only method of research. Modern wave models proved themselves to be good in application to any water area of the World Ocean in a wide range of spatiotemporal variability.

The scope of this study is

• to identify the strongest storms that have developed on the northeastern coast of the Black Sea over the past 45 years, from 1979 to 2023;

• to obtain statistical characteristics of the main parameters of wind waves (significant wave heights and wave energies) at selected points in the coastal zone of the Russian Black Sea coast (the inland part);

• to analyze the spatial features of the distributions of these characteristics.

We note that usually two main components can be distinguished in the structure of general surface waves, viz., pure wind waves generated from the local near-water field wind, and swell propagating outside the generation zones or at a phase velocity exceeding the wind speed. Under the conditions of the open ocean, swell waves may propagate for many hundreds or even thousands of kilometers. Swell can only be local in the enclosed Black Sea.

The statistical characteristics of the parameters of pure wind waves and swell differ. Compared to swell waves, wind waves have higher heights (usually for the conditions of the Black Sea) and shorter periods. As a result, the hydrodynamic consequences of the influence of wind waves and swell on beaches and structures in the coastal zone may be different. For example, low-frequency swell waves can generate dangerous phenomena in protected water areas (low-frequency oscillations). Recent research showed [7] that wind waves and swell affect differently the redistribution and transport of bottom sediments, determining either erosion or accumulation of bottom material.

In this regard, the analysis of storm activity on the northeastern coast of the Black Sea was performed taking into account the separation of the wave field into two components (wind wave and swell). Numerical modeling is the main method of research.

MATERIALS AND METHODS

Calculations of the climate characteristics of surface wave processes were carried out using the MIKE 21 SW state-of-the-art spectral wave model of the Danish Hydraulic Institute [8]. A detailed description of the model, verification details, and issues of model setup for automatic separation of sea wave components are presented in [9, 10].

We mention a few points.

• The MIKE 21 SW model implements the basic physical mechanisms associated with the generation, transformation, and decay of wind waves.

• The non-uniform computational grid of 10000 computational elements covers the waters of the Black Sea and the Sea of Azov.

• The initial wind fields represent a sample from the ERA5 dataset, distributed by the European Centre for Medium-Range Weather Forecasts (http://apps.ecmwf.int). The geographically calculated area is confined by coordinates $27°-42°$ E and $40.5°-47.5°$ N with a spatial resolution of $0.25°$, and a time resolution of 3 h.

• Fifty spectral frequencies are distributed in the range of wave periods from 1.6 to 17.3 s and follow the relationship $f_n = f_0 C^n$ ($f_0 = 0.055$ Hz, $C = 1.05$, $n = 1$, 2, ..., 50); the model resolution in directions is $11.25°$.

• The total wave motion is separated into components (pure wind waves and swell) using a criterion that takes into account the "age" of the waves.

The correctness of the model used is also confirmed by the experimental data obtained during the passage of the strongest storm in November 2023. The wave parameters were recorded by the ADCP RDI WH 600 kHz bottom station (Teledyne RD Instruments) located at a depth of 23 m in the traverse of the Blue Bay of the city of Gelendzhik (Fig. 1a) and being a part of the hydrophysical polygon of the Institute of Oceanology, Russian Academy of Sciences [11]. Figures 1b−1d show the time series of significant wave heights, spectral peak periods, and mean directions of wave propagation for November 2023. Blue dots represent the experimental data, and red lines depict the modeling results.

As follows from Fig. 1, the model used reproduces well the main parameters of surface waves (wave heights, periods, and directions). Unfortunately, on November 26, during an extreme storm, the ADCP station went out of order. The last significant wave height recorded by the instrument was 4.5 m. We note that the ADCP data themselves can hardly be considered as standard. Under stormy conditions, a huge amount of algae, flotsam, and simple debris (such as plastic, etc.) moves in the water column, serving as scatterers of acoustic signals. Nevertheless, the qualitative and quantitative (overall) correspondence of model data to field data suggests that the spectral wave model, covering the entire sea, is quite suitable for the study of wind waves in the coastal zone.

As a result of calculations, an array of spatial fields of the main parameters of general (mixed) wave processes, as well as its components over a climatic period of 45 years, from January 1979 to December 2023 was obtained. The temporal discretization of the fields is 1 h.

In our case, the main parameters we analyze will be the maximum significant wave heights during the
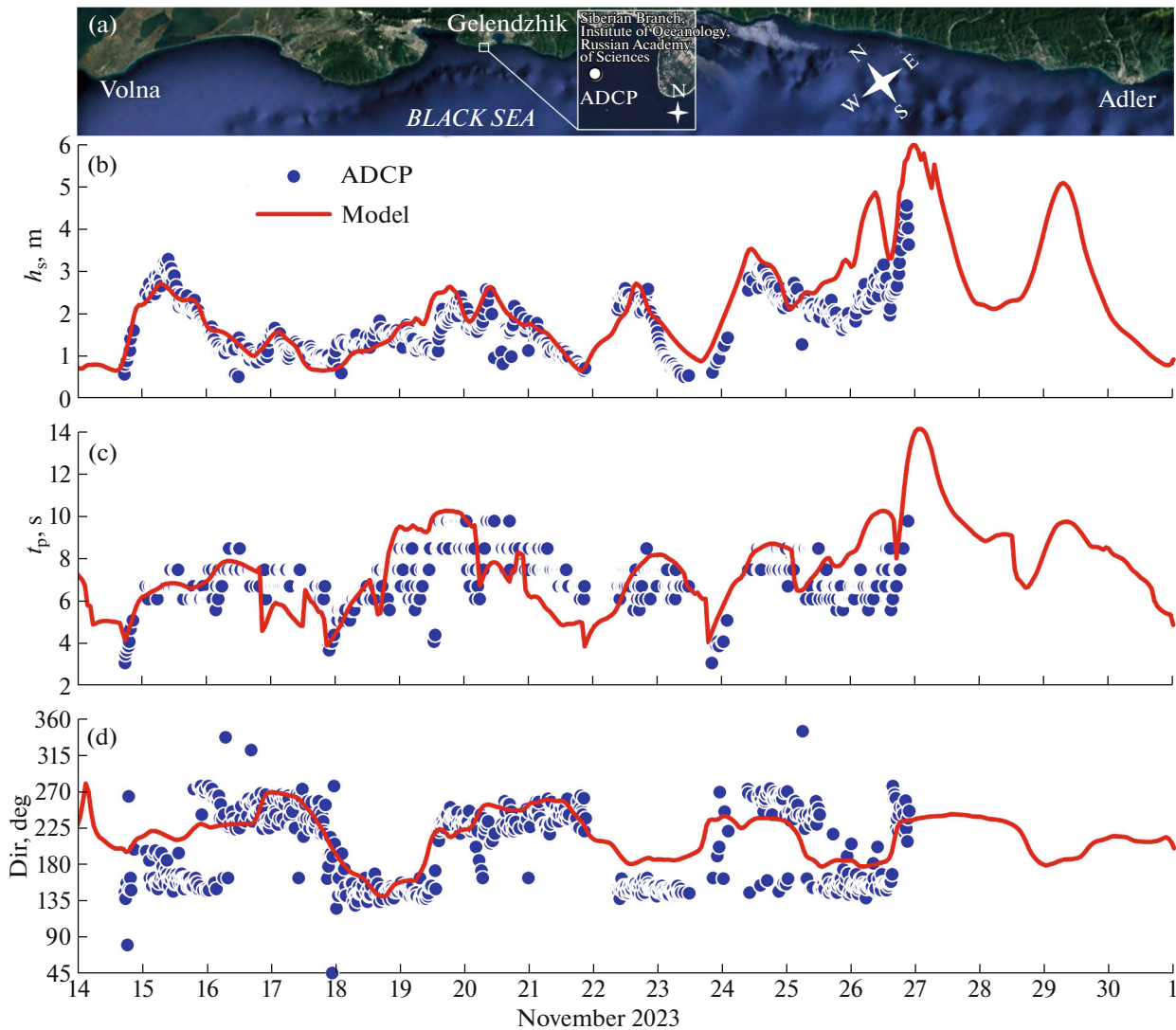
Fig. 1. Position of (a) ADCP station, (b) wave heights, (c) spectral peak periods, and (d) mean wave directions for November 2023.

storms, as well as the maximum wave energies. Note that wave power is a very indicative characteristic, since it is a function of two main integral wave parameters, viz., wave height and wave period. Power is an energy characteristic of storms and is estimated by the expression [12]

$$E = \frac{\rho g^2}{64\pi} h_s^2 t_e \approx \left(0.5 \, \frac{\text{kW}}{\text{m}^3 \text{s}} \right) h_s^2 t_e,$$

where h_s is the significant wave height, t_e is the so-called wave "energy" period, ρ is the density of water, and g is the acceleration of gravity. The "energy" period is a period of a monochromatic wave with power equivalent to the power of the given irregular wave; t_e is assumed to be equal to $0.9 t_p$ (t_p is the spectral peak period). Wave power is expressed in kilowatts per meter of the wave front.

At the first stage, we analyze the total wave activity on the northeastern shelf for the period of 1979−2023 and identify the storms during which the values of significant wave heights of mixed waves exceed 5 m. The threshold value of 5 m is taken for several reasons: (1) such heights of waves characterize strong agitation; (2) the number of the selected storms should ensure the statistical significance of the results.

Then we select the calculated points (a total of 21 points) located along the coastline, at which the maximum significant wave heights of mixed waves and components (pure wind wave and swell), as well as the corresponding maximum energies are found for each storm. The position of the calculated points is indicated in Fig. 2.

The straight-line distance between the extreme points (village of Volna and the city of Adler) is about 320 km. The water depth at each point is 23 m.
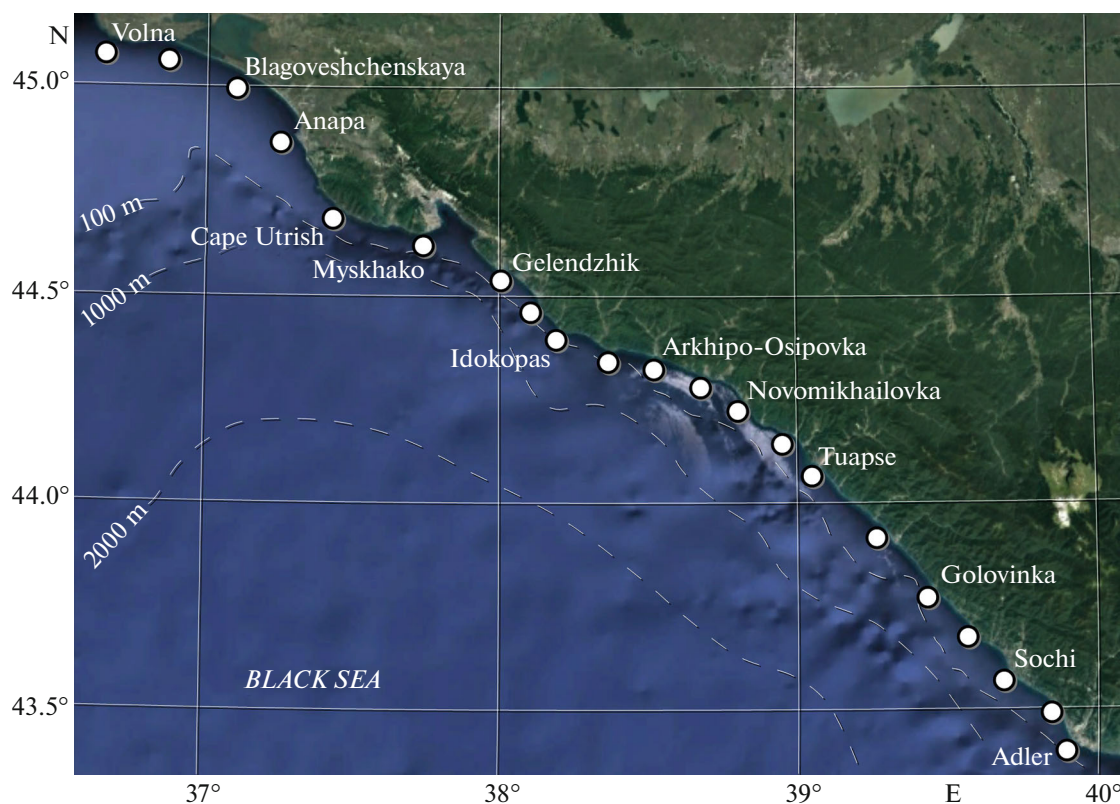
Fig. 2. Position of the calculated points along the northeastern coast of the Black Sea.

RESULTS AND DISCUSSION

Based on the results of numerical modeling over the past 45 years (from 1979 to 2023), 41 storms with exceedance of significant wave height of 5 m were identified. Table 1 presents the parameters of the five strongest storms.

The sixth strongest storm occurred in January 2007 and had the characteristics $E = 242$ kW/m and $h_s = 6.9$ m.

As follows from Table 1, two storms, in 2007 and 2023, significantly surpass other storms in their characteristics. Concerning the power, the 2007 storm dominates, while the maximum significant wave height is recorded for the 2023 event. It is quite likely

Table 1. Main characteristics of the strongest storms over a period from 1979 to 2023

No.	Year	Month	Maximum values	
			E, kW/m	h_s, m
1	2007	Nov.	518	9.0
2	2023	Nov.	510	9.1
3	1988	March	372	8.0
4	1992	Nov.	351	7.9
5	2000	Jan.	346	7.9

that the development of storm waves in these two storms corresponds to the maximum ideal combination of wave formation conditions: fetch length, duration, spatial stability, and air flow velocity.

The wave directions along the entire coastal area are naturally somewhat different, but they all have a common sector of wave action over deep water. The general direction of all storms is from the southwest to the west.

Note that, according to the studies by various authors [9, 13−15], the Black Sea is not among the most turbulent water areas. The average annual power of surface wave action in the Black Sea is about 3−4 kW/m. For comparison, the western coast of Scotland experiences storm wave action with average annual rates of ~40 kW/m [16].

Three out of the five strongest storms (Table 1) occurred in November. Figure 3 shows (a) the histogram of the number of storms by month and (b) the time of formation of each storm.

Figure 3a illustrates that winter is the most turbulent season (it is naturally expected), November is the most turbulent month of the year. Conspicuous is the fact that extreme storms did not happen in May, July, August, and October over the past 45 years. The period from 2000 to 2008 was the stormiest over the
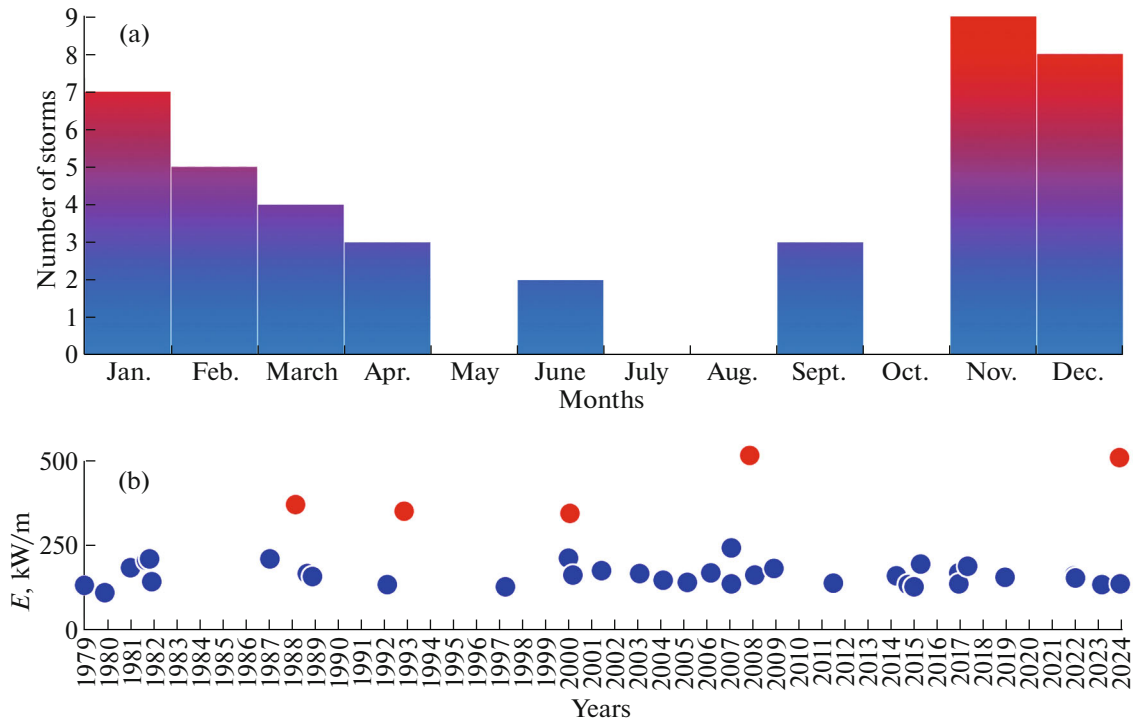
Fig. 3. Distribution of the number of storms (with $h_s > 5$ m) by months.
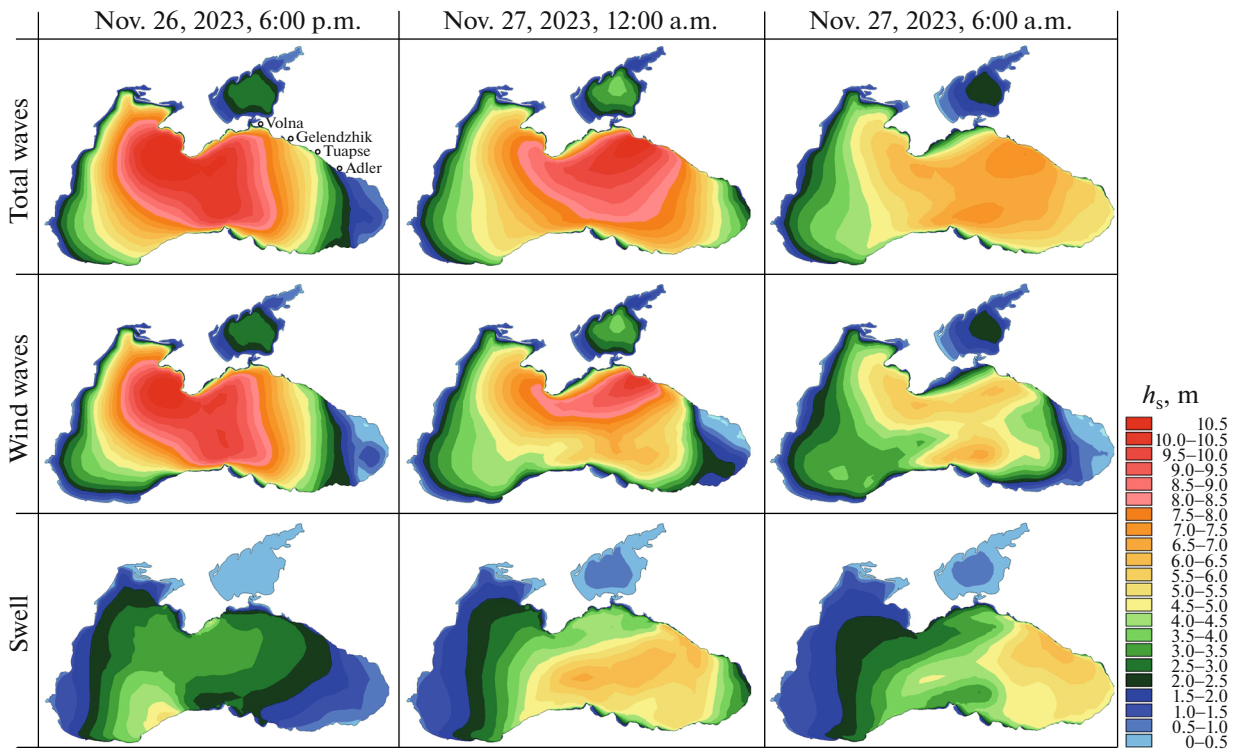

Fig. 4. Fields of significant wave heights in the Black Sea on November 26−27, 2023.

considered climatic timespan (Fig. 3b), accounting for almost one-third of all registered storms.

Figure 4 shows a typical pattern of transformation of storm wave fields in the Black Sea, which displays the maps of the distributions of significant wave heights of total (mixed) waves, as well as wave field components during the storm on November 26−27, 2023.
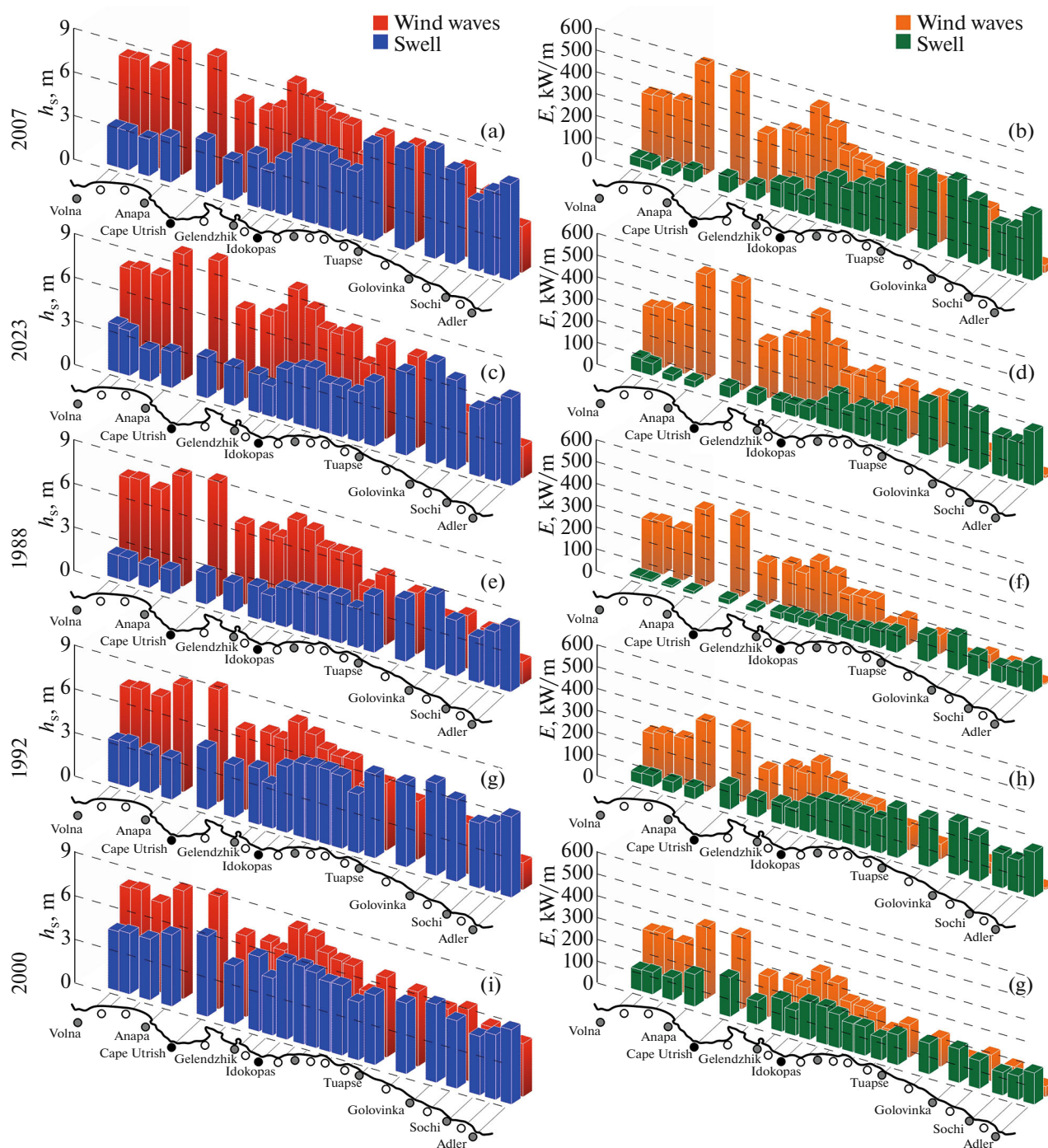
Fig. 5. Maximum values of significant wave heights (left column) and energies (right column) of pure wind waves and swell during the five strongest storms.

As is clear from Fig. 4, on November 26, the entire central part of the sea was affected by developing wind waves with heights of about 10 m. During the night from November 26 to 27, the main impact of the waves occurred on the northeast coast between Anapa and south of Gelendzhik. At the same time, in the eastern part of the Black Sea, a strong swell with heights up to

6 m was forming. By the morning of November 27, as the cyclone was weakening, the heights of wind waves decreased, but the swell was still noticeable in the Tuapse−Adler area.

Figure 5 illustrates the maximum values of significant wave heights and energies of wave field components at the calculated points of the coast for the five
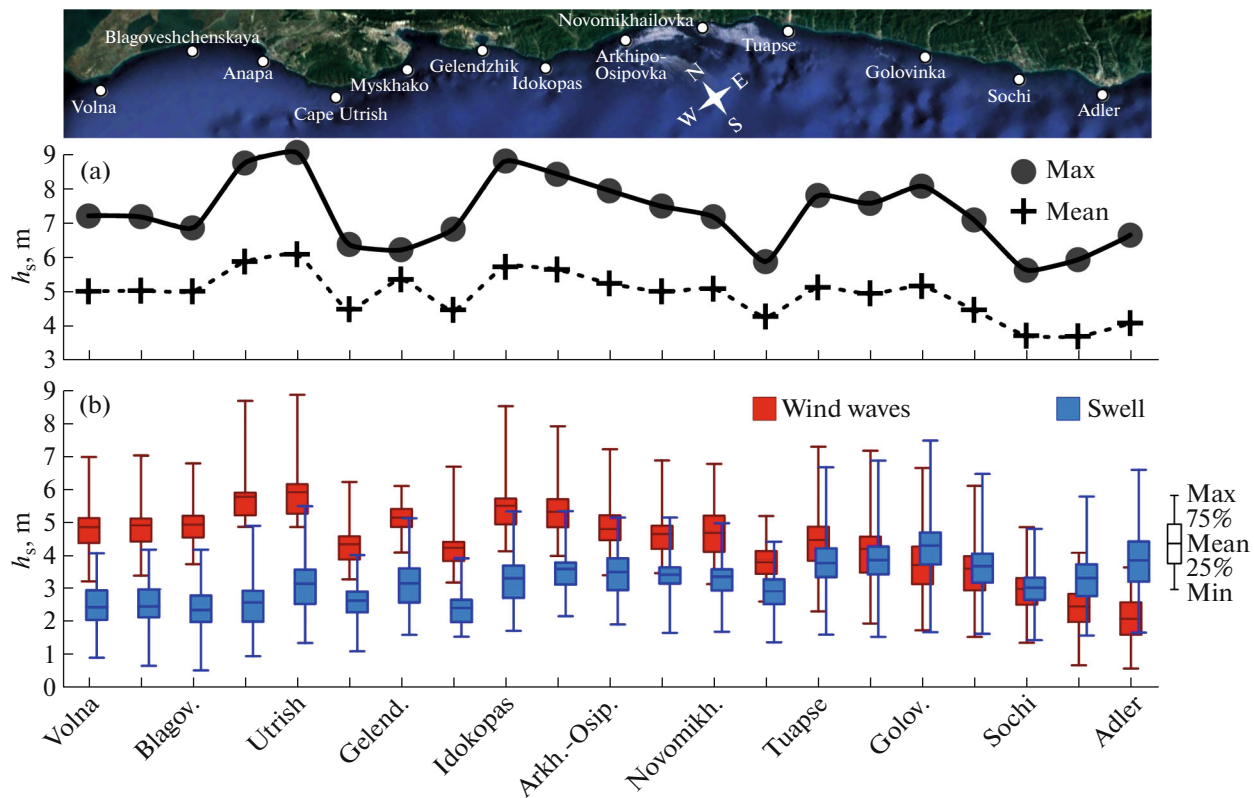
Fig. 6. Statistical characteristics of maximum significant wave heights in extreme storms over the period from 1979 to 2023; (a) total (mixed) waves, (b) wave components.

strongest storms from Table 1: (Figs. 5a, 5b) November 2007, (Figs. 5c, 5d) November 2023, (Figs. 5e, 5f) March 1988, (Figs. 5g, 5h) November 1992, and (Figs. 5i, 5j) January 2000.

Figure 5 clearly demonstrates the main spatial features of the distributions of the maximum storm characteristics. On the northeastern coast, the areas of the protruding Utrish and Idokopas capes, as well as Anapa, located northeast of Utrish, was hit the most by wind waves. Further to the southeast, the heights and energy of wind waves decrease, while the role of swell increases. As a rule, the most powerful swell occurs in the village of Golovinka, somewhat south of Tuapse. If, for all five extreme storms, the distribution pattern of maximum h_s and E of wind waves is in fact the same, the distribution pattern of swell characteristics is slightly different. This is likely due to changes in the external atmospheric conditions, leading to the formation of a new wave field and the decay of the old swell.

The storm in November 2007 (Figs. 5a, 5b) is characterized by extreme development of both wind waves and swell. In March 1988, there was a small swell (of course relatively small) during the third strongest total (mixed) wave storm (Figs. 5e, 5f). In January 2000 (fifth storm, Figs. 5i, 5j), Cape Utrish was hit by the storm with the highest values of wind waves and swell.

However, the data in Fig. 5 allow us to identify the main tendencies of transformation of mixed wave components along the entire coastal zone: when moving from the northwest (village of Volna) to the southeast (the city of Adler), the heights and energy of wind waves decrease, while those of swells, on the contrary, increase.

Figures 6 and 7 show, respectively, several statistical characteristics of the maximum significant wave heights and energies during extreme storms over a period from 1979 to 2023 for the total (mixed) waves and the wave field components (pure wind waves and swells). Recall that the statistics were obtained after processing the data for 41 storms. The mean and maximum values are presented for mixed waves; mean, minimum, and maximum, and the 25th and 75th percentiles of distributions are provided for wind waves and swells.

Figures 6 and 7 show that the most significant wave heights occur during extreme SW−W storms in the areas of Anapa, Utrish, and Idokopas. In these areas, significant wave heights of mixed waves may reach 9 m and an energy exceeding 500 kW/m. For comparison, the maximum wave energy of Hurricane Wilma over the Gulf of Mexico in 2005 was 814 kW/m [17]. The average heights of mixed waves for the entire coast vary within 4−6 m (Fig. 6a), with average energy of about
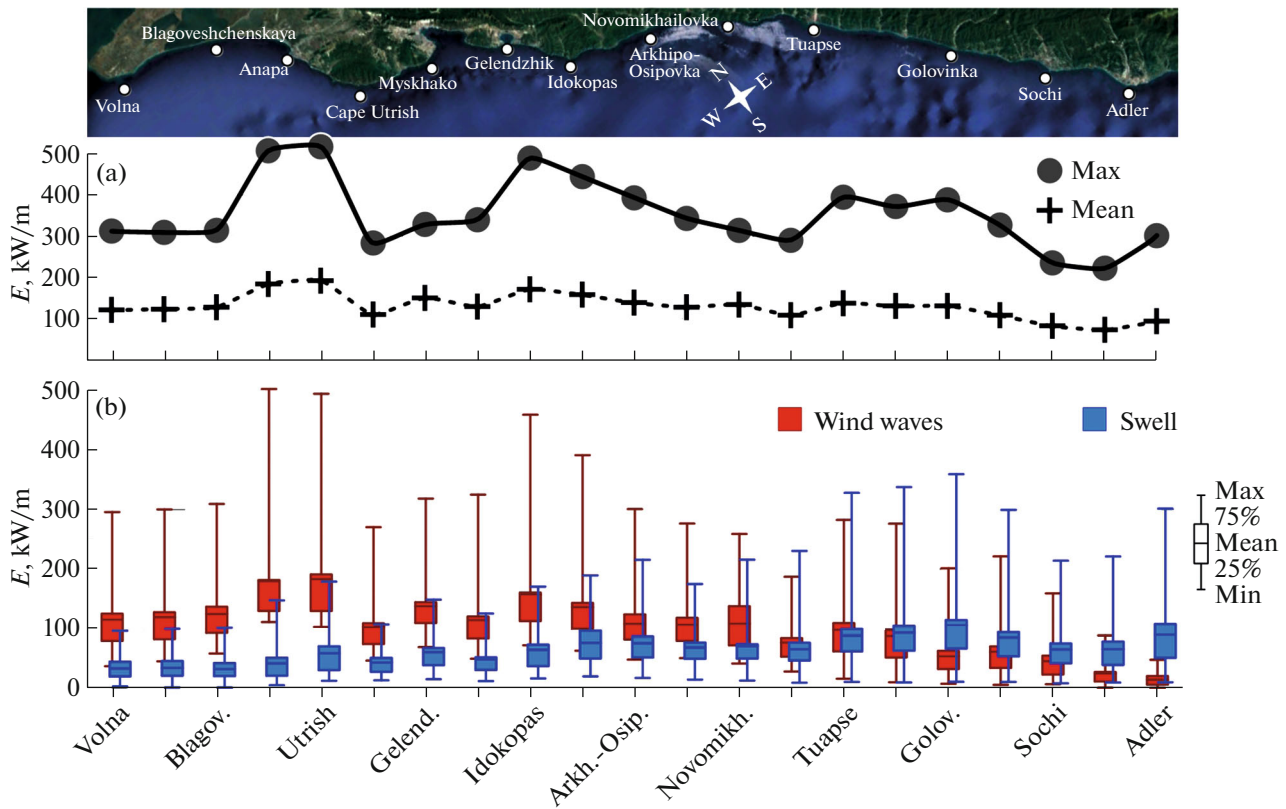
Fig. 7. Statistical characteristics of maximum energies in extreme storms over the period from 1979 to 2023; (a) total (mixed) waves, (b) wave components.
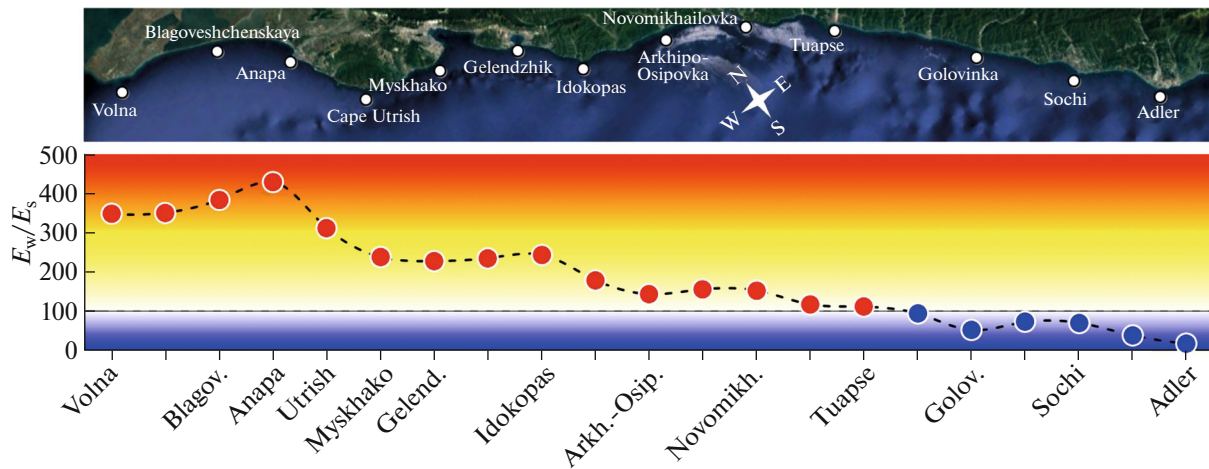

Fig. 8. Ratio of average energies of wind waves and swell along the coast.

150 kW/m (Fig. 7a). The most hazardous wind waves are also formed in the vicinity of Anapa, Utrish, and Idokopas, and swell, in the area from Tuapse to Golovinka, as well as in the area of Adler (Figs. 6b, 7b). In Golovinka, swells may reach 7.5 m, while in Adler, 6.5 m.

The comparatively small spreads between the 25th and 75th percentiles indicate that halves of the samples are quite closely grouped around the mean value.

The mean values of wind wave heights and energy have a common tendency to decrease when moving from the northwestern part of the coast to the southeastern part, while for the swell they increase. Figure 8 is quite indicative in this case, showing the ratios of average energies of wind waves E_w and swell E_s along the northeastern coast of the Black Sea.

Figure 8 displays several relatively homogeneous segments along the considered coastline. In the storm

wave structure, wind waves absolutely dominate on average (this is important) between Volna and Anapa. Between capes Myskhako and Idokopas, the contribution of wind waves to the total wave power exceeds the contribution of the swell by a factor of 2−2.5. Between Arkhipo-Osipovka and Tuapse, the power of pure wind waves exceeds the power of the swell only slightly. South of Tuapse, the contribution of the swell becomes dominant. Two areas stand out on the scale of the entire coast: in the vicinity of Anapa, the wave climate is almost entirely determined by wind waves, while in Adler, by the swell.

CONCLUSIONS

The aim of this study was to investigate extreme storm waves on the northeastern shelf of the Black Sea over a climatic time period. Numerical modeling was the main method of research. The object of this study was the coastal zone from Volna (the Kerch Strait area) to Adler.

The calculations of the climatic characteristics of surface waves were carried out using the MIKE 21 SW state-of-the-art spectral wave model. As a result of the calculations, hourly fields of spatial distributions of the main wave parameters were obtained across the entire Black Sea water area over the period from January 1979 to December 2023, i.e., for the past 45 years. The analysis was carried out taking into account the separation of the wave field into two components: pure wind waves and the swell.

The main results are the following:

(1) Over the past 45 years, the northeastern coast of the Black Sea was hit by 41 storms with significant wave heights exceeding 5 m.

(2) Two storms in November 2007 and November 2023 greatly surpass the other storms in their characteristics. Significant wave heights of mixed waves reached 9 m, and the energies exceeded 500 kW/m. It is likely that these values are the maximum for the level of development of storm waves in the coastal zone.

(3) The most turbulent month of the year is November. No extreme storms were recorded in May, July, August, and October over the past 45 years. The period from 2000 to 2008 was the stormiest, accounting for almost one-third of all recorded storms.

(4) Average heights of mixed storm waves along the entire coast vary from 4 to 6 m, and the average energies are about 150 kW/m.

(5) The highest wave heights (within the considered coastal area) are observed in the areas of Anapa, Utrish, and Idokopas.

(6) The average values of heights and energies of pure wind waves tend to decrease in the direction from the northwestern part of the coast to the southeastern, while for swells, on the contrary, they tend to increase.

(7) Several relatively homogeneous segments with different levels of development of pure wind waves and swell are found in the coastal zone. Wind waves completely dominate in the structure of the average storm wave between Volna and Anapa. The contribution of wind waves to the total wave power between capes Myskhako and Idokopas exceeds the contribution of swell by a factor of 2−2.5. The power of pure wind waves between Arkhipo-Osipovka and Tuapse slightly exceeds the power of the swell. Further south of Tuapse, the contribution of the swell becomes predominant.

(8) Two regions are distinguished in terms of the ratio of the contribution of wind waves and swell along the entire coast: in the vicinity of Anapa, the overall wave climate is almost fully determined by wind waves, while in Adler, it is determined by the swell.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. V. V. Efimov and O. I. Komarovskaya, *Extreme Wind-Induced Waves in the Black Sea: Atlas* (EKOSI-Gidrofizika, Sevastopol, 2009) [in Russian].

2. A. B. Polonsky, V. V. Fomin, and A. V. Garmashov, Rep. Natl. Acad. Sci. Ukraine **8**, 108−112 (2011).

3. E. S. Nesterov, *Extreme Waves in Seas and Oceans* (IG-SOTsIN, Obninsk, Moscow, 2015) [in Russian].

4. E. Rusu, Front. Mar. Sci. **3**, 95 (2016).
https://doi.org/10.3389/fmars.2016.00095

5. G. Van Vledder and A. Akpınar, in *Proc. 35th Int. Conf. on Coastal Engineering,* Ed. by P. Lynett (Antalya, 2016), Vol. 35, pp. 199−212.

6. B. V. Divinsky, V. V. Fomin, R. D. Kosyan, and Yu. D. Ratner, Oceanologia **62** (1), 23−30 (2019).
https://doi.org/10.1016/j.oceano.2019.06.003

7. B. V. Divinsky and R. D. Kosyan, Oceanologia **62** (2), 1902019.199 (2020).
https://doi.org/10.1016/j.oceano.2019.11.002

8. DHI Water and Environment, 2007, MIKE 21, Spectral Wave Module.

9. B. Divinsky and R. Kosyan, Cont. Shelf Res. **136**, 1−19 (2017).
https://doi.org/10.1016/j.csr.2017.01.008

10. B. Divinsky and R. Kosyan, Oceanologia **60**, 277−287 (2018).
https://doi.org/10.1016/j.oceano.2017.11.006

EXTREME WIND WAVES ON THE NORTHEASTERN SHELF OF THE BLACK SEA 1233

11. A. G. Zatsepin, A. G. Ostrovskii, V. V. Kremenetskii, et al., Izv., Atmos. Oceanic Phys. **50** (1), 16−29 (2014). https://doi.org/10.1134/S0001433813060157

12. G. Boyle, *Renewable Energy: Power for a Sustainable Future,* 2nd ed. (Univ. Press, Oxford, 2004).

13. A. Akpinar and M. Ihsan Kömürcü, Appl. Energy **101**, 502−512 (2013).

14. B. Aydogan, B. Ayat, and Y. Yuksel, Renew. Energy **57**, 436−447 (2013).

15. L. Rusu, Energies **8**, 10370−10388 (2015).

16. *Wave energy in the UK: Status review and future perspectives*, in *Renewable and Sustainable Energy Reviews* (Elsevier, 2021). https://doi.org/10.1016/j.rser.2021.110932

17. M. Ulloa, R. Silva, and I. Mariño-Tapia, Sustainability **15**, 7414 (2023). https://doi.org/10.3390/su15097414

Translated by L. Mukhortova