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ОЦЕНКА РЕСУРСОВ ВОЛНОВОЙ ЭНЕРГИИ БАЛТИЙСКОГО МОРЯ И ПРИБРЕЖНОЙ ЗОНЫ КАЛИНИНГРАДСКОЙ ОБЛАСТИ

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На основе данных ретроспективных расчетов параметров ветрового волнения проведена оценка ресурсов энергии ветровых волн в Балтийском море. Расчеты параметров волнения выполнены с помощью спектральной модели SWAN и данных о ветре из реанализа NCEP/CFSR (CFS2) 1979–2015 гг. Расчеты проводились на прямоугольной сетке 0.05°. Были получены карты распределения среднемноголетней мощности энергии ветровых волн на метр фронта волны за период 1979–2015 гг. Ее максимальные значения достигают 6–6.5 кВт/м и расположены в центральной и юго-восточной частях Балтийского моря, для прибрежной зоны Калининградской области они составляют 3–4 кВт/м. Произведен анализ сезонной и межгодовой изменчивости мощности волновой энергии для двух точек, расположенных в открытом море и в прибрежной зоне юго-восточной Балтики. Наибольшие показатели приурочены к осенне-зимнему периоду, наименьшие – к весенне-летнему. Рассчитаны показатели среднемноголетней обеспеченности волновой энергии для нескольких пороговых критериев. Так, обеспеченность волновой энергии с пороговым значением 1 кВт/м для центральной части моря составляет 55–60%.

Ключевые слова: волновая энергия, Балтийское море, мощность волновой энергии, моделирование волнения, Калининградская область, SWAN, обеспеченность волновой энергией.

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WAVE ENERGY RESOURCES OF THE BALTIC SEA AND COASTAL ZONE OF THE KALININGRAD REGION

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Based on the data of numerical simulations of the wind wave parameters, the wave energy resources of the Baltic Sea were estimated. Calculations of the wave parameters were performed using the SWAN spectral model and the wind data of NCEP/CFSR (CFS2) reanalysis from 1979 to 2015. The simulations were realised using a rectangular grid with a spatial resolution of 0.05°. The maps of the average annual wave energy flux for the period 1979–2015 were plotted. The maximum values of which reach 6–6.5 kW/m and appear in the Baltic Proper and in the South-Eastern Baltic. For the Kaliningrad Region, the wave energy flux is 3–4 kW/m. The analysis of the seasonal and interannual variability of the wave energy flux for two points located in the open sea and in the coastal zone of the South-Eastern Baltic was carried out. Seasonal variability of the wave energy flux is very high: the energy flux in the winter months is several times greater than in the summer period. The average long-term probability of exceedance of the wave energy for several thresholds was calculated. The probability of exceedance of the wave energy with a threshold 1 kW/m in the Baltic Proper is 55–60%.

Keywords: wave energy flux, Baltic Sea, wave power, wave modelling, Kaliningrad Region, SWAN, probability of exceedance of wave energy.

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Introduction. Currently, there is an abundance of studies devoted to renewable energy sources. [1–4]. In particular, attention is paid to the studies of the sea and ocean wave energy [5–8]. Power which propagate by sea waves ("wave energy flux") is the energy flow through a vertical strip of a unit width and infinite depth, perpendicular to the direction of propagation; while energy flux value is measured in kW per unit of wave-crest length (kW/m). Compared with wind and solar energy, wave energy has a much higher surface power density [2]; therefore, the study of wave energy resources is a pressing challenge. The distribution of wave energy is heterogeneous spatially and temporally. Designing energy systems or devices for a specific water area, driven by wave energy, requires detailed calculation or experimental data of the parameters of waves in a selected area. Since the 1990s, mathematical modelling methods have been applied for wave energy estimation with the use of various meteorological reanalyses [9–12].

The Baltic Sea wave climate is a focus of numerous studies that consider both the whole sea and its separate regions [13–21]. For the wave climate of the Baltic Sea increased storm activity in the autumn-winter months, a high spatial and temporal heterogeneity of wind waves, and a predominance of relatively short and steep waves are characteristic [13, 17]. The annual average significant wave height in the Baltic Proper reaches 1.2–1.3 m [17, 18, 21]. Here, significant wave height (H_s) is defined traditionally as the mean wave height (trough to crest) of the highest third of the waves. The major part of storms comes from the west, while H_s, in this case, increases up to 5–6 m [12, 16, 17, 22]. The maximum H_s was observed during the Gudrun hurricane in 2005 and, according to various estimates, amounted to 8–9 m [14, 23].

It is difficult to compare wave energy resources of the Baltic Sea with, for example, energy of the Barents or Okhotsk Seas, where the annual average wave energy flux can reach 20–25 kW/m [2]. According to [2], the average wave energy flux in the Baltic Sea are 7–8 kW/m. However, there is a great interest to the study of wave energy flux in the Baltic Sea, because developed countries have access to this sea, and a large number of potential consumers of wave energy are concentrated in the area [4, 24]. For example, in Denmark, an experimental wave converter with a capacity of 500 kW [25] was launched in operation. Displacement of sediments and coastal erosion are also associated with wave energy, which is a compelling issue for the Baltic Sea [26, 27].

General estimates of the wave energy flux in the Baltic Sea are presented in [22]. According to the authors' calculations, the average annual wave energy flux for the Baltic Proper reaches 5–6 kW/m [22].

For the east coast of the Baltic Proper, the average wave energy flux over a 37-year period is about 1.5 kW/m (up to 2.55 kW/m) according to estimates in [24, 28]. As for the interior of the Gulfs of Finland and Riga, the values are 0.7 kW/m. In total along the coast, the energy resources of the waves for the entire eastern coast of the Baltic Sea are about 1.5 GW [28].

An analysis of the wave energy flux distribution in the coastal zone of Lithuania was presented in [11, 29]. The average annual wave energy flux there is 1.21 kW/m. In the autumn-winter season, it is more intense ~1.4–2.4 kW/m, and in spring and summer, it is ~0.7–0.9 kW/m.

The present study provides an analysis of the seasonal and inter-annual variability of the wave energy flux for the Baltic Sea, and in more detail for the coastal zone of the Kaliningrad Region based on a continuous wave reanalysis for the period 1979–2015. The probability of exceedance of wave energy flux was calculated for the threshold values of 0.5, 1, and 2 kW/m.

Data and methods. To estimate the wave energy flux, we used the wave parameters' calculation data for the Baltic Sea, simulated by the SWAN spectral wave model [30] for the period 1979–2015. The calculations were performed on a rectangular grid with a resolution of 0.05°. The results' output time step was 3 hours. The wind data for wave modelling were obtained from the NCEP/CFSR reanalysis (1979–2010) with a spatial resolution of ~0.3° [31] and NCEP/CFSv2 (2011–2015) reanalysis with a resolution of ~0.2° [32]. The time step in these reanalyses is 1 hour. The transition from one reanalysis data to another was executed in the following way: – the NCEP/CFSR reanalysis data for the last 3 days of 2010 was interpolated onto a grid with a 0.2° step corresponding to the NCEP/CFSv2 reanalysis. Further, the calculation was made on the wind fields data with a step of 0.2°, starting from December 29, 2010, to December 31, 2015. A more detailed description of the configuration of the wave model is given in [15, 16, 33]. As was shown in [33], the wave heights calculated on the NCEP/CFSR reanalysis data are in a good agreement with the field data (the correlation coefficient is 0.93, and the root mean square error is 0.37 m), as the systematic error (Bias) is small, therefore, the wind data didn't undergo any specific adjustments. For example, the study [34] for the Black Sea, reported that the distribution of the systematic error for NCEP/CFSR reanalysis is notably erratic in space and time, and the correction implementing, in fact, degrades the results of wave simulation. The quality of wave parameters' simulation in the case of lengthy NCEP/NCAR reanalysis is significantly lower: the root mean square error is 0.71 m, and the correlation coefficient is 0.82 [14, 33], therefore this reanalysis was not used.

The wave energy flux (P, kW/m) is calculated in the model for each node of the computational grid using the equation:

$$P^2 = Px^2 + Py^2, \tag{1}$$

where $Px = \rho g \iint CxE(\sigma, \theta) d\sigma d\theta$; $Py = \rho g \iint CyE(\sigma, \theta) d\sigma d\theta$, ρ – water density, g – acceleration of gravity, $E(\sigma, \theta)$ – wave energy in spectral space, σ – wave energy frequency; θ – wave energy propagation angle; Cx, Cy – wave group velocities in space x, y.

The wave energy flux has a direction and it is a vector quantity. However, because of strong variability, it is necessary to take recourse to the variable averaging over a certain time window (month, year or longer). The average direction of the wave energy flux was not considered in this article since this indicator is not critical in the context of the energy resources assessment. A more accurate approach in analysing the energy distribution direction considers specific storms, which is not part of this study objective.

Next, the average values of H_s, length, wave period and wave energy flux for the entire period (37 years) were calculated. The inter-annual averages of energy flux were also calculated separately for each month. For two points in Kaliningrad water area, the wave energy flux averages for each year and inter-annual averages for each month from 1979 to 2015 were estimated. These indicators allow the estimation of its seasonal and inter-annual variability. For the wave farm construction, the most important is to have data on the stability of the wave energy flow over time. For these purposes, the probability of exceedance of wave energy was calculated for the threshold values of 0.5, 1, 2 kW/m per unit of wave-crest length. Probability of exceedance is the ratio of the number of values when the wave energy flux exceeds a predetermined threshold to the total number of terms of the entire series [9, 35]. Thus, the probability of exceedance of wave energy for the threshold «more than 1 kW/m» is calculated by the equation (2):

$$O_{1kW} = m/n \cdot 100, \tag{2}$$

where m is the number of values from the series when the wave energy flux exceeded 1 kW/m per unit of wave-crest length, n – total.

Probability of exceedance of wave energy varies in space and is calculated for each node of the computational grid. Calculations were carried out for the entire series, and also for particular months of the period (1979–2015).

Due to the fact that for the parameters' modelling of the waves, the presence of ice in the Baltic Sea was not taken into account, the average long-term maps for the Bothnian and Gulf of Finland appear to contain errors. Therefore, in a subsequent analysis, these areas were not considered, and they are marked with hatching on the maps.

Results. Average inter-annual values of the H_s, the average period and the wavelengths were obtained by averaging the data series from 1979 to 2015 with a time step of 3 hours for the entire water area of the Baltic Sea (fig. 1, *a–d*, see insert). The zone of maximum H_s of 1.2–1.25 m is located in the Baltic Proper and South-Eastern Baltic. The maximum annual-average value of the wave period was 4.1 s, for wavelengths – 24 m (fig. 1, *a–d*). For the Kaliningrad Region, the average wave height Hs is 0.8–0.9 m in the proximity of the coastal zone and increases up to 1–1.1 m at a distance of 20–30 km off the coast (fig. 1, *d*). For the analysis of the inter-annual and seasonal variability, two points were chosen: near the coast, T-1 (56° N; 19.5° E); and in the open sea, T-2 (55.1° N; 20° E), where the highest average multiyear H_s are observed (fig. 1, *d*).

Also, the long-term averages of the wave energy flux for the entire simulation period and for individual months were calculated with the simulation data. The most intense wave energy is concentrated in the Baltic Proper and in the South-Eastern Baltic with values of 6–6.5 kW/m (fig. 2, *a*, see insert). The obtained quantitative estimates are generally consistent with the results of studies [22, 28].

Inter-annual average values for August and November were considered to analyse seasonal variability of the wave energy flux. In August, the maximum wave energy flux of about 3 kW/m is located in the south-eastern part of the Baltic Sea (fig. 2, *b*). In November, the values increase to 10 kW/m in the open part and to 4–6 kW/m in the coastal zone in the south-eastern part of the sea (fig. 2, *c*).

Average values of energy flux do not reflect its stability over time, which is necessary for the generation of electricity. In this regard, the probability of exceedance of wave energy was calculated for the threshold values of 0.5, 1, 2 kW/m. This indicator allows estimation of the time when the energy flux of waves exceeds a predetermined threshold value in percent. The calculations were carried out for the entire series of data (37 years). Figure 3 (*a–b*, see insert) shows the probability of exceedance of wave energy for thresholds of 0.5, 1 and 2 kW/m. In the Baltic Proper, the probability of wave energy flux exceeding 0.5 kW/m is greater than 70%. For the coastal zone, this indicator, as a rule, is lower, and for the Gulf of Finland it does not exceed 40–50%.

The probability of wave energy exceeding 1 kW/m amounts to 60% only in a small area in the central part of the sea, and in the other areas, is less than 40–50%. In the Baltic Proper and in the South-Eastern Baltic, the probability of wave energy exceeding 2 kW/m is observed 40–45% of the time. More stable is the wave energy flux of the 0.5 kW/m in the Baltic Proper and in the South-Eastern Baltic only (fig. 3, *a–b*). The probability of wave energy flux exceeding 1 kW/m in the Baltic is significantly lower than in the Barents Sea, where this indicator amounts to 80–90% [35]. However, in comparison with the Black Sea, where the average annual energy flux 1 kW/m is only 50% [36], the probability of exceedance of wave energy in the Baltic Sea is slightly higher.

Wave energy has high seasonal variability, therefore the assessment of probability of exceedance of wave energy for different seasons has been carried out. Figure 4 (*a–b*, see insert) presents probability of exceedance of wave energy for 0.5 kW/m in August and November. In the central part of the sea, probability of exceedance for 0.5 kW/m in August is about 60%, whereas in November it is more than 85% (fig. 4, *a–b*). The number of storms increases in the winter period, which not only leads to a rise in the average values of the wave energy flux but also to an increase in exceedance probability. This information is necessary for taking into account seasonal changes for the wave power farms. However, it should be noted that during storms and extremely high waves, the operation of wave converters is not safe. For example, for the above mentioned experimental buoy wave power station in Denmark, wave height of 2.5 m is optimal for energy generation [25]. When the height of the waves reaches 3 m, then the floats, fixed on a special mounting, automatically rise above the water surface, and the operation of the power station stops for the duration of the storm.

In addition to seasonal, inter-annual variability was analysed. In this regard, the average annual wave energy flux was calculated for two points located in the open sea and in the coastal zone (at a distance of 10 km from the coast) (fig. 1, *d*). The annual average values from the coastal station (T-1) varies within the range of 3–8.9 kW/m; values for the open sea (T-2) are higher – 4.7–9.9 kW/m (fig. 5). The minimum was observed in 1996, while in most cases the change from year to year does not exceed 2 kW/m. The inter-annual variation in wave energy flux is high and must be taken into account. Negative linear trends for both points are statistically insignificant for the entire period; a local maximum is observed at the beginning of the 90s.

At the next stage, the variability analysis of monthly mean values of the wave energy flux was carried out for the same two points. During the considered period, from 1979 to 2015, the maximum wave energy flux was about 38 kW/m for the T-2 in the open sea in January 1983, and the second maximum of 35 kW/m was recorded in January 1993 (fig. 6). For the coastal point, the maximum in 1995 was slightly lower – 32 kW/m. Seasonal variability is very high. Almost every year during the winter months, the average monthly energy flux

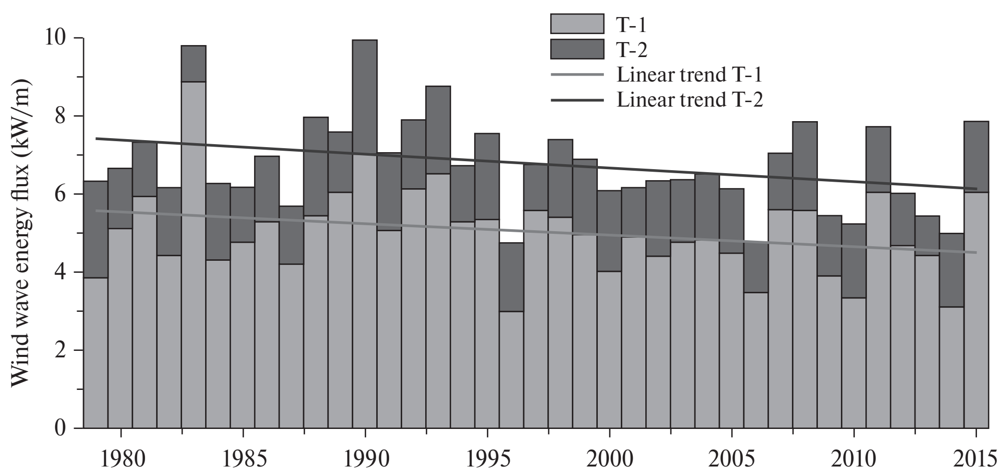

Рис. 5. Среднегодовые значения мощности волновой энергии в двух точках T-1 и T-2 в юго-восточной части Балтийского моря.

Fig. 5. Average annual wave energy flux at two points T-1 and T-2 in the south-eastern part of the Baltic Sea.

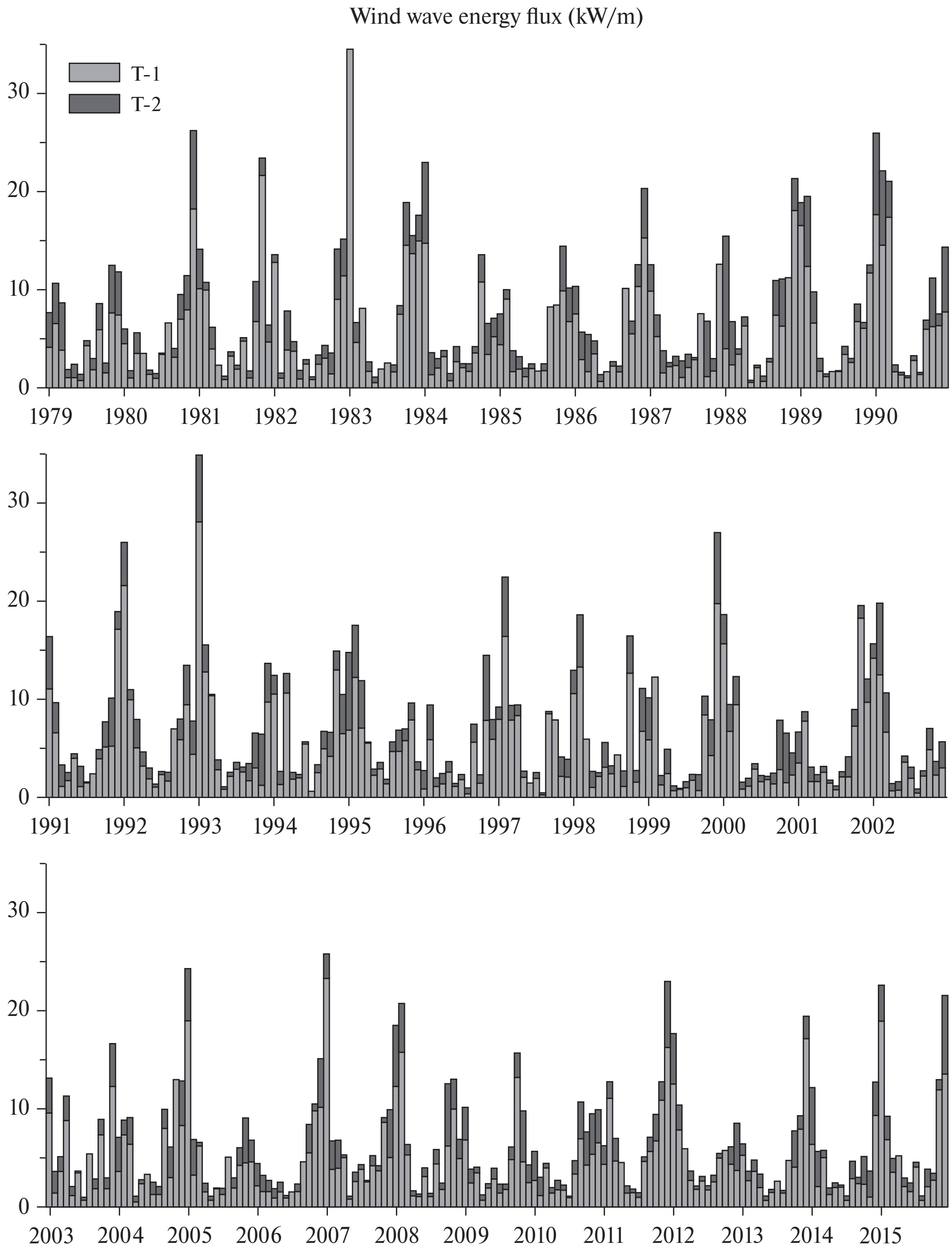

Рис. 6. Среднемесячные значения мощности волновой энергии, кВт/м с 1979 по 2015 гг. для двух точек в юго-восточной части Балтийского моря.

Fig. 6. Monthly mean values of wave energy flux, kW/m from 1979 to 2015 for two points in the south-eastern part of the Baltic Sea.

of waves exceeds 10 kW/m. Every few years, the flux of wind energy exceeds 20 kW/m. The minima refer to the summer months (1.5–3 kW/m).

In the open sea, the wave energy flux is on average 1.5 times higher than in the coastal zone. The greatest difference was determined for the winter months, while in the summer the energy flux differs only slightly, and is low at both points (fig. 6).

A separate analysis of the wave energy flux distribution was performed for the coastal zone of the Kaliningrad Region. Fig. 7, *a*, see insert presents data on the average annual wave energy flux. Immediately near the coast, values of 4 kW/m were recorded, and at a distance of 10–15 km – more than 5 kW/m. Papers [24, 28] present the average estimates about 1.4–1.8 kW/m for the Kaliningrad Region, which is significantly lower than in our calculations. This discrepancy can be explained by the use of a more modern wind reanalysis with higher spatial resolution in our case.

In November, the average wave energy flux in the coastal zone of the Kaliningrad Region is 6–7 kW/m, and in August – 2 kW/m (fig. 7, *b–c*).

The average annual probability of exceedance of wave energy for a threshold value of 0.5 kW/m is 55–60% (fig. 7, *d*). For November, probability of exceedance increases up to 70–75%, and for August it decreases to 45–50% (fig. 7, *e–f*).

Conclusion. Data on the distribution of the wave energy flux in the Baltic Sea and in the water area of the Kaliningrad Region were obtained on the basis of the numerical modelling results for the period 1979–2015.

The maximum average annual energy wave flux is 6–6.5 kW/m and it is located in the Baltic Proper and South-Eastern Baltic. In August, the maximum wave energy flux of 3 kW/m is obtained for the south-eastern part of the Baltic Sea. In November the energy flux values reach 10 kW/m in the open part and 4–6 kW/m in the coastal zone of the Kaliningrad Region.

In the Baltic Proper, the average annual probability of exceedance of wave energy for 0.5 kW/m threshold is above 70%, in August – about 60%, and in November – more than 85%.

The inter-annual variability is analysed with the data on the average annual wave energy flux for two points located in the South-Eastern Baltic at a distance from the coast and near it. In general, the inter-annual variability of the wave energy flux is large. Average annual values for a point in the open sea are within the range of 4.7–9.9 kW/m, for a point in the coastal zone it is 3–8.9 kW/m.

The maximum monthly average energy flux of 38 kW/m is located in the open part of the sea and was observed in January 1983. During the winter months, the average monthly energy flux exceeds 10 kW/m, except for the winter season of 2005–2006 and 2012–2013. Every few years there are maxima of more than 20 W/m. The minima are confined to the summer months – 1.5–3 kW/m.

On average, in the open sea, the wave energy flux is 1.5 times higher than in the coastal zone. The greatest differences are observed in the winter months, and in the summer the differences were minimal.

For the Kaliningrad Region near the coast, the average annual wave energy flux is 4 kW/m, and at a distance of 10–15 km – more than 5 kW/m. Near the coast, the average energy flux is amplified in November up to 6–7 kW/m and decreased in August down to 2 kW/m.

In general, the energy resources of the waves in the Baltic Sea, in comparison with the Barents or Okhotsk Seas, are lower. In the Kaliningrad Region 60% of the time, the probability of exceedance of wave energy for 0.5 kW/m, and 50% of the time, for threshold 1 kW/m for the Baltic Proper and in the South-Eastern Baltic.

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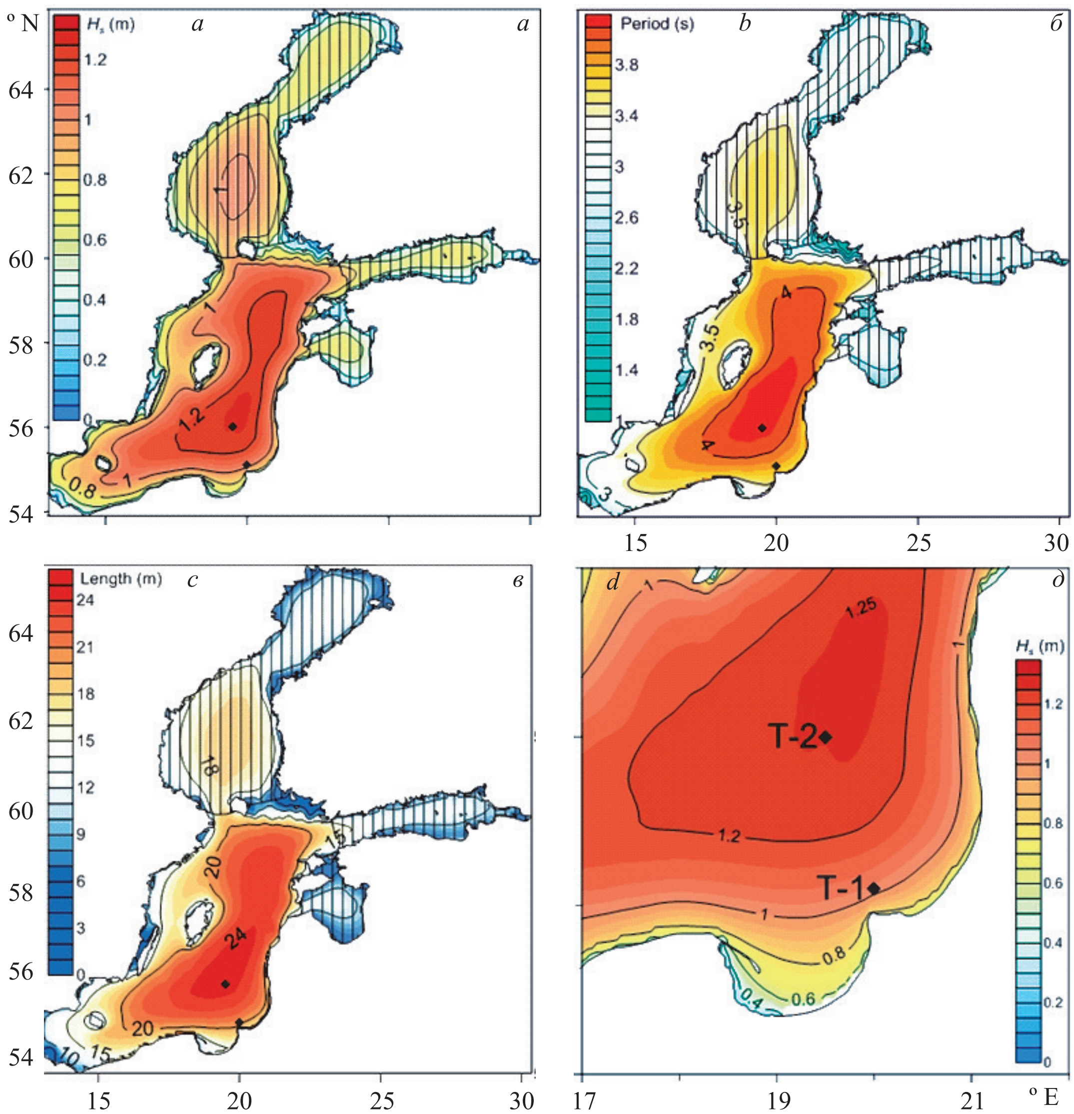

Fig. 1. The average multiyear (for the period 1979—2015) wave height H_s (*a*), average period (*b*), average wavelength (*c*) in the Baltic Sea. Here and below, diamonds denote points T-1 and T-2. Hatching (hereafter) indicates the areas with frequent sea ice.

Рис. 1. Среднемноголетняя (за период 1979—2015) высота волн H_s (*а*), средний период (*б*), средняя длина волн (*в*) в Балтийском море. Здесь и далее ромбами обозначены точки Т-1 и Т-2. Штриховкой (здесь и далее) обозначены зоны, где результаты моделирования возможно содержат ошибки, из-за морского льда.

К статье *Мысленков С. А., Медведева А. Ю.* Оценка ресурсов волновой энергии...

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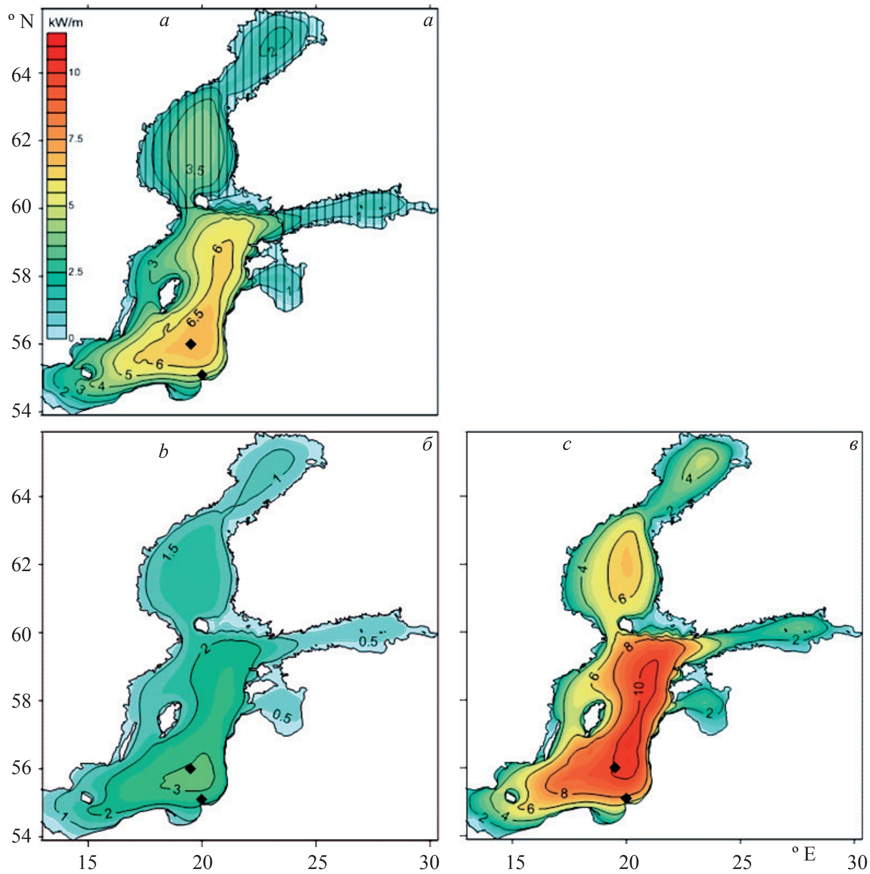

Fig. 2. Annual averages (1979—2015) for the wave energy flux values for the whole year (*a*), for August (*b*) and November (*c*).

Рис. 2. Среднемноголетние (1979—2015 гг.) значения мощности волновой энергии для всего года (*а*), для августа(*б*) и ноября (*в*).

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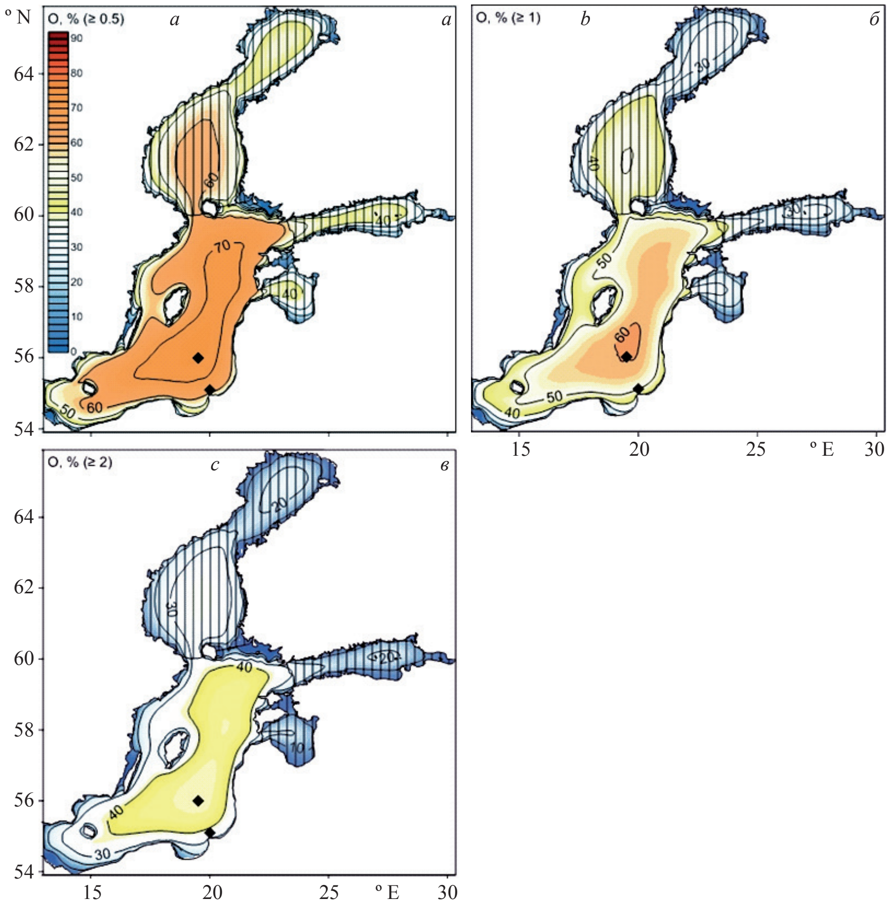

Fig. 3. Average long-term probability of exceedance of wave energy for threshold values of 0.5 kW/m (*a*), 1 kW/m (*b*), 2 kW/m (*c*).

Рис. 3. Среднемноголетняя обеспеченность волновой энергией для пороговых значений 0.5 кВт/м (*а*), 1 кВт/м (*б*), 2 кВт/м (*в*).

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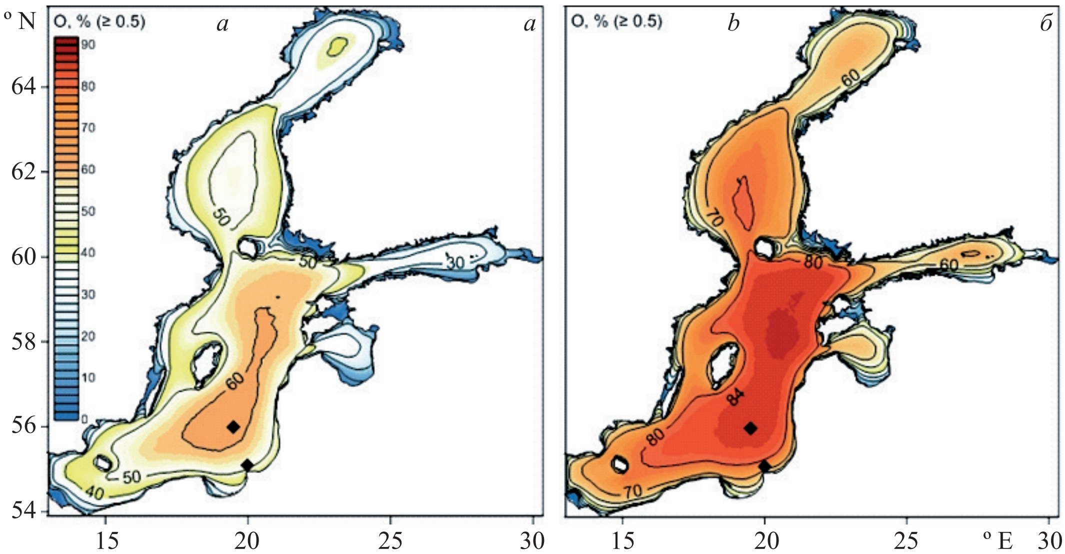

Fig. 4. Probability of exceedance of wave energy for a threshold value of 0.5 kW/m in August (*a*) and November (*b*).

Рис. 4. Обеспеченность волновой энергией для порогового значения 0.5 кВт/м в августе (*а*) и ноябре (*б*).

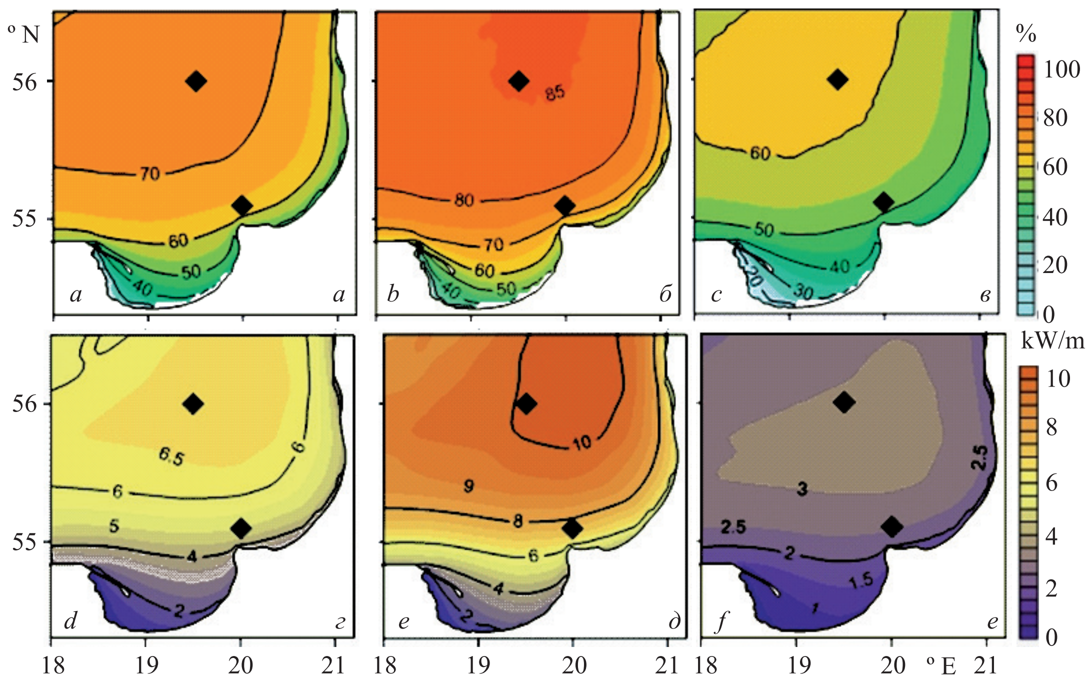

Fig. 7. Average annual wave energy flux for the whole year (*a*), for November (*b*) and August (*c*). Average inter-annual probability of exceedance of wave energy > 0.5 kW/m for the whole year (*d*), for November (*e*) and August (*f*).

Рис. 7. Среднемноголетняя мощность волновой энергии для всего года (*а*), для ноября (*б*) и августа (*в*). Среднемноголетняя обеспеченность волновой энергией > 0.5 кВт/м для всего года (*г*), для ноября (*д*) и августа (*е*).