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FUTURE WAVE HEIGHT DYNAMICS IN THE KAZAKH PART OF THE CASPIAN SEA

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ABSTRACT

The development of oil and gas fields in the Caspian region, year-round navigation at sea, and the need to preserve biodiversity have led to a growing interest in comprehensive studies of the Caspian Sea, including wind disturbance. This study aims to investigate the process of wind waves at sea and calculate its spatial and temporal changes in the future based on numerical modeling using the SWAN spectral-wave model. Calculations of wave height projection into the future up to 2050 using climate model data from the NEX-GDDP-CMIP6 dataset for two greenhouse gas emission scenarios showed that up to 2050 the maximum wave heights can vary from 1.1 m to 4.0 m at SSP1-2.6 with the highest values in 2023, 2029, 2042; from 1.3 m to 4.1 m at SSP5-8.5 with the highest values in 2029, 2033, 2050. In the Kazakhstan part of the sea, significant and strong waves are possible in the future (for the period 2022...2050). Because by 2050 the wave height may reach 6 m in the Middle Caspian Sea it is necessary to build protective dams in the areas of oil fields and settlements, as well as strengthening and reconstruction of previously built.

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1. INTRODUCTION

Wind-driven waves dominate movements in the marine environment and are a major factor affecting coastal populations, ecosystems, coastal infrastructure and maritime activities, including oil field development and shipping [1,2]. Storms can generate strong waves and currents, which in turn affect the location and strength of surf waves [3, 4].

Coastal areas are subject to the combined action of several factors: sea level changes, increasing frequency of natural phenomena and coastal degradation. The development of technical means for the exploitation of offshore waters (oil and gas production), the marine fleet and the need to preserve biodiversity have led to a growing interest in a comprehensive study of the Caspian Sea, including hydrometeorological processes.

In this context, information on hazardous and natural hydrometeorological phenomena, such as gale force winds, high waves, sea level rise and fall, etc., is required when carrying out work at sea, when designing open water and coastal structures, in order to ensure the safe navigation of the civil and military fleet.

All calculations related to wave parameters are hampered by the lack of long-term observational series, which in turn are carried out visually, and therefore the various wave characteristics are mainly determined by statistical or numerical modelling.

The aim of this work is to analyze the process of wind waves in the Caspian Sea and to predict their spatial and temporal changes in the future based on numerical modelling.

In economic, transport and infrastructure terms, the Caspian Sea region is of strategic interest to the Caspian littoral states. In Kazakhstan, the port of Aktau was built on the coast in 1963 and the port of Kuryk in 2014. The oil and gas industry are developing successfully

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and there are three major oil and gas fields in Kazakhstan: Tengiz, Karachaganak and Kashagan.

Forecasting ocean and sea waves is a very difficult task in coastal and water engineering in general due to their high degree of randomness. Several authors, especially scientists from the Caspian countries, have studied wave processes in the Caspian Sea, such as Abuzyarov Z.K. [5…7], Nesterov E.S. [8], Lopatukhin L.I. [9], Myslenkov S.A. [10], Arkhipkina V.S. [11], Lebedev S.A. [12], Kostyanoy A.G. [13], etc.

According to some research, modern methods of numerical modelling, their development and an increase in the amount of remote sensing data make it possible to analyze the dynamic processes occurring in the Caspian Sea quite accurately [14…18], including wave processes.

Studies conducted by Dobrovolsky A.D. and Zalogin B.S. on various hydrometeorological characteristics of the Caspian Sea have determined that periods of high waves exceeding 6 points are observed from November to March [19].

According to data from the Kazhydromet observation network, the highest waves in the Kazakh part of the Caspian Sea, reaching 4.5 m, were recorded in Aktau [20]. Studies conducted by Kazakhstan specialists for the waters near the port of Aktau in 2017…2018 showed that the average wave height reaches 1 m, and the maximum wave height reaches 4 m [21].

Numerous researchers have adapted hydrodynamic and wave models for the Caspian Sea waters [21...29]. The automated system of wind wave prediction for the Caspian, Black and Azov Seas, developed at the Russian Hydrometeorological Centre, is based on the software code of the WaveWatch III spectral model. It has shown a sufficiently high prediction quality, comparable with another foreign systems [25...26]. Bruneau N. and Toumi R. [27] carried out wave calculations on the coupled ocean-atmosphere-wave system using WRF, ROMS and SWAN. The results showed that multimode wave states are observed in the Caspian Sea. For example, weak waves less than 50 cm in height are common in the northern part and are directed to the east and west. Rusu E., Onea F. [28] modelled the wave characteristics using ERA-Interim wind reanalysis for 2005-2010, the result of which showed that the maximum wave heights are formed in the central part of the sea, so in the water area adjacent to Kazakhstan the maximum wave height reached 2.84 m.

In 2014, R.M. Mammadov developed the Hydrometeorological Atlas of the Caspian Sea [30], and in 2015, the Russian Geographical Society of the Faculty of Geography of Lomonosov Moscow State University developed the Electronic Atlas of the Caspian Sea, which includes oceanographic research (water temperature, salinity, ice conditions, wave climate). According to the Atlas, there are several areas in the Caspian Sea where the highest waves form throughout the year: near the Absheron Peninsula and the central part of the Southern Caspian, as well as in the eastern part of the Middle Caspian [31].

The purpose of this work is to perform numerical calculations and determine wave height values for the Kazakh part of the Caspian Sea.

2. MATERIALS AND METHODS

2.1. Description of study area

The Caspian Sea is the largest enclosed body of water in the world, located at the junction of Europe and Asia. Its shores are bordered by the Russian Federation, the Republic of Kazakhstan, Turkmenistan, the Islamic Republic of Iran, and the Republic of Azerbaijan [24].

The main orographic units of the coast are in the north - the pre-Caspian lowland, and in the west - the mountains of the Eastern Precaucasus and the Greater Caucasus, with a narrow coastal lowland [32,33]. The sea is divided into three parts: the shallow northern part (with an average depth of less than 10 m), the middle part (up to 788 m), and the southern part, which is the deepest, with a maximum depth of 1025 m [33].

The size of the Caspian Sea depends on fluctuations in sea level, which are determined by the characteristics of the water balance [34]. According to calculations for 2023, with an average sea level of minus 28.87 m BS [35], the sea area was 357 900 km^2, and the water volume amounted to 77 675 km^3. The catchment area of the sea is 3.1 million km2, of which about 30 % is in the undrained areas [36]. The Caspian Sea is fed by more than 130 rivers (including Volga, Zhaiyk, Terek, Kura, etc.), which together supply about 270…300 km^3 of water annually [28…33]. The Volga River alone accounts for about 80–85% of the inflow, making it the dominant factor in the water balance [37...38].

The Caspian Sea spans several climatic zones: the north is characterized by a sharply continental climate, whereas the south is influenced by subtropical conditions. The mean annual air temperature ranges from 6...8 °C in the north to 14...16 °C in the south. Precipitation varies from less than 200 mm along the eastern coasts to more than 1700 mm in the mountainous regions of the west and south. Annual evaporation from the sea surface exceeds river inflow, rendering the hydrological balance highly sensitive to climate change [36].

Wind regimes play a decisive role in wave generation. In the northern and eastern Caspian, strong northerly and north-easterly winds dominate, often exceeding 15...20 m/s during storms. In the central and southern parts, winds are more variable, contributing to the development of long-fetch waves. During winter, the northern Caspian freezes, with ice thickness reaching 40...70 cm, whereas the central and southern parts remain ice-free [36].

2.2. Datasets

Changes in wave height in coastal waters were analyzed using data from the national monitoring network. At present, visual changes in wave height are monitored at 7 marine stations in Kazakhstan: Kulaly Island, Fort-Shevchenko, Saura, Aktau, Isan, Kuryk and Fetisovo [39] (Figure 1).

Figure 1. *Study area. Location of hydrological stations Kazakhstan marine observing network*

Qualitative data on bathymetry represents a crucial prerequisite for effective wave forecasting. In this study, the GEBCO bathymetry dataset was employed at a resolution of 450 m, encompassing 2648 depth measurements within the Caspian Sea region [40].

The quality of the wind fields is a determining factor in the outcome of wave modelling. The daily mean wind speeds were derived from climate model data of the NEX-GDDP-CMIP6 dataset, which consists of downscaled global climate scenarios (0.25° by 0.25° data resolution) derived from General Circulation Model runs conducted as part of the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Additionally, two greenhouse gas emission scenarios (SSP1-2.6 and SSP5-8.5) known as the socio-economic shared pathways (SSP) were incorporated into the analysis [41].

From the total NEX-GDDP-CMIP6 dataset of 35 models, 27 models consisting of daily average data for 365/366 days per year for two scenarios, SSP1-2.6 and SSP5-8.5, for the Caspian Sea area were selected for evaluation of wind speed variation and subsequent application to wind wave calculations (Table 1).

Table 1
Description of CMIP6 models

Model name	Simulation Centre, country	Horizontal resolution
TaiESM1	AS-RCEC (Taiwan)	0.9x1.25
NorESM2-MM	NorESM (Norway)	1.25◦× 0.942◦
NorESM2-LM	NorESM (Norway)	2.5◦× 1.895◦
NESM3	NUIST (China)	1.875◦× 1.865◦
MPI-ESM2-0	MRI (Japan)	1.125◦× 1.121◦
MPI-ESM1-2-LR	MPI (Germany)	1.875◦× 1.865◦
MPI-ESM1-2-HR	MPI (Germany)	0.9375◦× 0.935◦
MIROC6	MRI (Japan)	1.4◦× 1.4◦
MIROC-ES2L	MRI (Japan)	2.8125◦× 2.79◦
KIOST-ESM	KIOST (Republic of Korea)	2.2 × 2.2
IPSL-CM6A-LR	IPSL (France)	2.5◦× 1.27◦
INM-CM5-0	INM (Russia)	1.5 × 2.0
INM-CM4-8	INM (Russia)	1.5 × 2.0
GISS-E2-1-G	GISS (USA)	2.0° × 2.5°
GFDL-ESM4	NOAA	1.0 × 1.3
FGOALS-g3	CAS (China)	2.3 × 2.0
EC-Earth3-Veg-LR	EC-EARTH (Netherlands/Ireland)	0.7 × 0.7
EC-Earth3	EC-EARTH (Netherlands/Ireland)	0.7 × 0.7
CanESM5	CCCma (Canada)	2.8125◦× 2.79◦
CNRM-ESM2-1	CNRM (France)	1.4 × 1.4
CNRM-CM6-1	CNRM (France)	1.4◦× 1.4◦
CMCC-ESM2-1	CNRM (France)	1.4 × 1.4
CESM2	NCAR (USA)	1.25◦× 0.94◦
BCC-CSM2-MR	BCC (China)	2.8 × 2.8
ACCESS-ESM1-5	Beijing Climate Center	1.2 × 1.8
ACCESS-CM2	CSIRO (Australia)	1.25◦× 1.875◦
CMCC-CM2-SR5	CMCC (Italy)	1.25◦× 0.94◦

2.3 Methods

The third-generation SWAN spectral wave model [42...43], developed by Delft University of Technology (Netherlands), was used to calculate wind wave dynamics in the Caspian Sea.

In the linear wave model, the sea surface height is adequately represented by a stationary Gaussian process. The sea surface height at a given point in time can be expressed by the following equation (1):

$$\eta(t) = \sum_i \mathrm{a_i} \cos\left(\sigma_i \mathrm{t} + \alpha_i\right) \tag{1}$$

where, η·- sea surface height, ai – amplitude of the i-th wave component, σi – relative frequency in radians or the circular frequency of the i-th wave component in the presence of the ambient current, αi– random phase of the i-th wave component [42,43].

The model is founded upon the resolution of the wave field energy balance equation in spectral space (2), and incorporates the non-linear interactions of the three waves.

$$\frac{\delta N}{\delta t} + \frac{\delta c_x N}{\delta x} + \frac{\delta c_y N}{\delta y} + \frac{\delta c_\sigma N}{\delta \sigma} + \frac{\delta c_\theta N}{\delta \theta} = \frac{S_{tot}}{\sigma} \tag{2}$$

where, N – specific spectral density, x, y – spatial coordinates, t – time, σ – wave frequency, θ – wave angle, cσ,cθ - propagation velocity in spectral space, Stot– source function, which includes physical processes such as wave generation due to wind energies, nonlinear transfer of wave energy by harmonic interactions, wave reduction due to foam and splash formation, friction on the bottom and wave reversal at critical depth [42,43].

In the model, the significant wave height is defined as (3) [43]:

$$H_s = 4^{\sqrt{\iint E(\omega,\theta) d\omega d\theta}} \quad (3)$$

where, E (ω, θ, σ) – dispersion density spectrum, ω – absolute frequency in radians, k – wave number.

The SWAN model is primarily dependent on two key input parameters: bathymetry and wind characteristics.

A comparison of CMIP6 model data with actual data on daily mean wind speed at stations along the Caspian Sea coast for the period 1995 to 2014 revealed that the modelled annual mean wind speeds are in close alignment with the actual data.

The statistical criterion for evaluating the accuracy or applicability of climate change projection data is as follows:

mean absolute error:

$$\mathrm{MAE} = \frac{1}{N} - \sum |X - Y| \quad (4)$$

root mean square error:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N} \sum (X - Y)^2} \quad (5)$$

efficiency coefficient:

$$E = 1 - \frac{\Sigma (x_i - y_i)^2}{\Sigma (x_i - \bar{x})^2} \quad (6)$$

index of agreement:

$$d = 1 - \frac{\Sigma (x_i - y_i)^2}{\Sigma (y_i - \bar{x}) + (x_i - \bar{x})^2} \quad (7)$$

Based on wind data from CMIP6 models using the SWAN model, maximum wave height values were simulated for the Kazakh part of the Caspian Sea. For the period between 1995 and 2014, the maximum wave height ranged from 2.29 m (ACCESS-CM2) to 3.53 m (EC-Earth3) for Fort-Shevchenko and from 2.47 m (INM-CM4-8) to 4.59 m (EC-Earth3) for Aktau. Figure 2 presents a comparison between the maximum wave height based on actual data and calculated data using the ERA5 reanalysis and CMIP6 models.

The correlation coefficients between the actual and calculated values when applying these CMIP6 models exhibited fluctuations within the same limits for the selected stations. For Aktau, the fluctuation ranged from -0.8 to 0.8, while for Fort-Shevchenko, it ranged from -0.9 to 0.8.

The analysis of statistical evaluation criteria showed that MAE values range from ~0.6 to 1.5 m. The lowest MAE values are observed in the MRI-ESM2-0, MPI-ESM1-2-LR, and MIROC6 models, especially for the Fort Shevchenko and Aktau stations. The highest MAE values (>1.3 m) are observed in the EC-Earth3 and ACCESS-ESM1-5 models, especially for Aktau.

The RMSE values range from 0.8 to 1.8 m. The lowest RMSE values are observed for MRI-ESM2-0, MPI-ESM1-2-LR, and MIROC6, confirming their better performance in reproducing wave characteristics.

The efficiency coefficient values are negative for almost all models, indicating that the modeling results are worse than simply using the mean of the observations. Higher values (less negative, closer to zero) are obtained for MRI-ESM2-0, MIROC6, and MPI-ESM1-2-LR, which confirms their relative advantage.

Among the models considered, the most stable and least erroneous results for maximum wave height are provided by MRI-ESM2-0, MIROC6, and MPI-ESM1-2-LR.

The observation station Fort-Shevchenko is better represented by the models, while Aktau shows the largest errors and the worst efficiency coefficients, which may be related to the more complex wave conditions in the southern Caspian Sea.

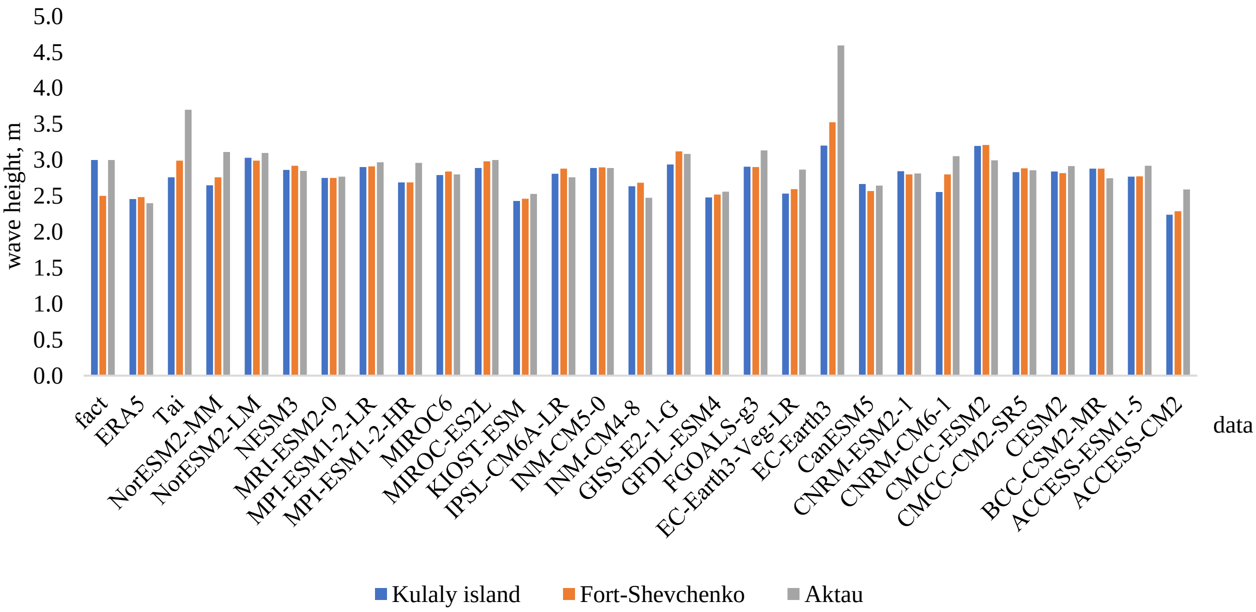

Figure 2. *Graph of actual and calculated maximum wave height for the period 1995...2014*

Following an analysis of the degree of correlation between observed and computed wave heights, it was determined that 13 models exhibited the highest correlation with the actual data: ACCESS-ESM1-5, BCC-CSM2-MR, CESM2, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, EC-Earth3-Veg-LR, INM-CM4-8, KIOST-ESM, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, NESM3. It is important to note that coastal wave observations are made visually, rather than through the use of automated instruments.

In the context of offshore operations, the maximum wave height represents the most critical wave characteristic, as storm waves have the potential to inflict significant damage to coastal and offshore structures, in addition to ships at sea. Subsequently, projections of future wave height change up to 2050 were calculated for maximum wave heights under two climate change scenarios, SSP1-2.6 and SSP5-8.5, of the ensemble of 13 CMIP6 models.

3. RESULTS AND DISCUSSION

In the Kazakh part of the sea, the occurrence of waves with a height of 2 meters or above was documented on 265 occasions between the years 1980 and 2021. The predominant wave direction is westerly, occurring with a frequency of 30% over the course of the study period. It is noteworthy that the north-west and south-east directions also exhibited a notable frequency, at 26% and 25%, respectively [20, 21, 44].

The three most significant areas within the Kazakh section of the Caspian Sea, including Fort-Shevchenko, Aktau, Kuryk, were identified as being of particular importance with regard to the socio-economic sphere of the Mangistau and Atyrau regions of the Republic. In addition, these areas are home to a number of strategic maritime installations, including ports and hydropower stations.

The maximum wave heights from CMIP6 models off Fort Shevchenko for the future up to 2050 under the climate change scenario SSP1-2.6 were found to range from 1.1 m to 4.0 m (Figure 3). The highest values of 3.6 m in 2023 (CNRM-CM6-1) and 4.0 m in 2029 (NESM3) were observed. In the case of Fort Shevchenko, the maximum wave heights that can be expected from 2015 to 2050 under the SSP5-8.5 scenario range from 1.4 m to 3.4 m, with the highest values of 3.3 m in 2029 (MRI-ESM2-0), 2033 (KIOST-ESM) and 3.4 m in 2050 (MPI-ESM1-2-HR).

Figure 3. *Projection of maximum wave height to 2050 under scenarios a) SSP1-2.6 and b) SSP5-8.5*

The maximum wave heights for Aktau predicted by CMIP6 models for the future up to 2050 indicate that under the SSP1-2.6 climate change scenario, maximum wave heights may vary from 1.3 m to 3.6 m, with the highest values of 3.6 m in 2023 (CNRM-CM6-1), 2029 (NESM3), and 2042 (CESM2) (Figure 3). In the context of the SSP 5-8.5 scenario, the potential range of maximum wave heights is estimated to vary between 1.5 m and 4.1 m between 2015 and 2050. The highest values are projected to occur in 2029 (MRI-ESM2-0).

The maximum wave heights projected by CMIP6 models at Kuryk for the future to 2050 indicate that under the SSP1-2.6 climate change scenario, maximum wave heights could range from 1.3 m to 3.9 m, with peaks reaching 3.9 m in 2029 (Figure 3). (NESM3), and under the SSP5-8.5 to 2050 scenario, maximum wave heights could vary from 1.4 m to 4.0 m, with maximum values of 4.0 m in 2029 (MRI-ESM2-0).

Figure 4 illustrates the projected spatial variation of maximum wave height in the Caspian Sea region for the 2023...2050 period. The distribution of wave height in the Caspian Sea area for the future, as projected by the SSP1-2.6 climate change scenario, indicated a mean wave height ranging from 0.65 m to 1.25 m with a mean value of 1.02 m. The maximum value was observed to range from 1.86 m to 5.58 m.

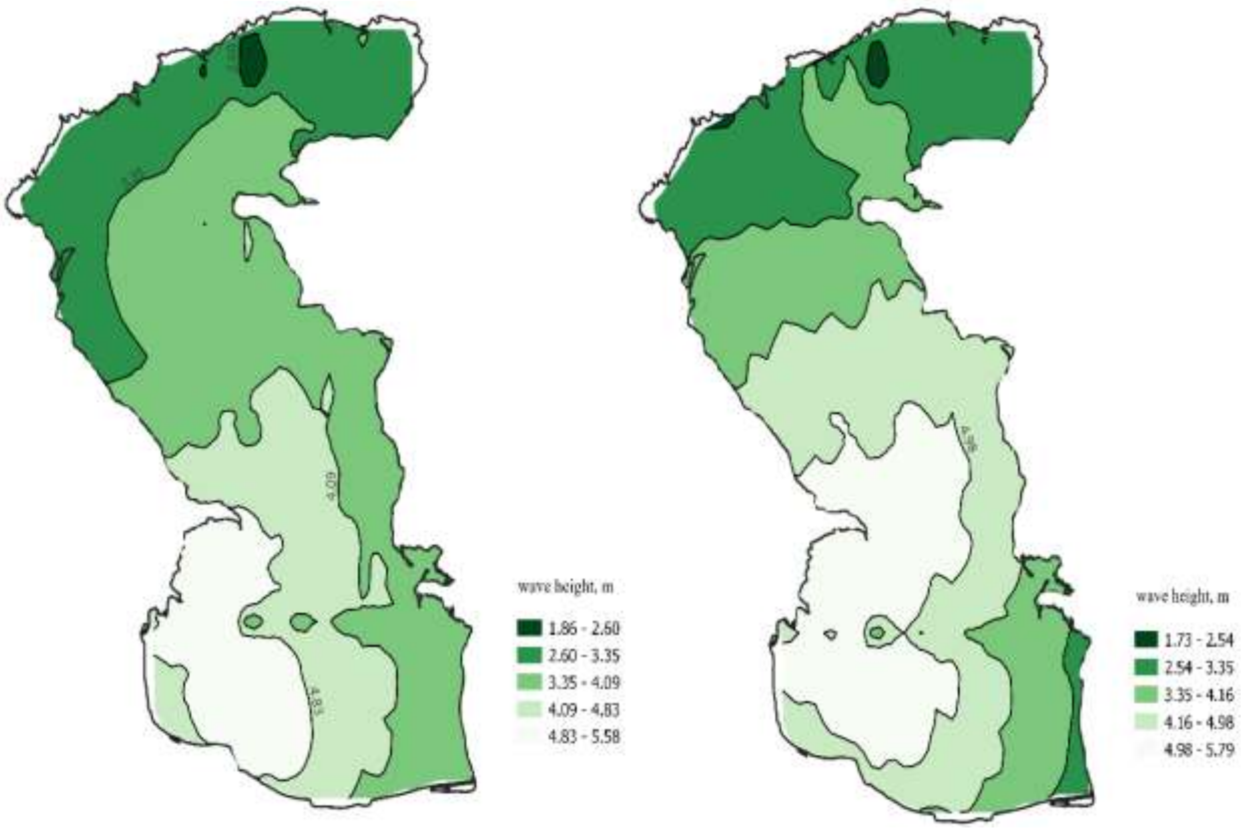

Figure 4. *Map of the distribution of maximum wave height based on the projection of SSP1-2.6 (left) and SSP5-8.5 (right) for 2023...2050*

In the Kazakhstan sector of the sea, the occurrence of substantial and robust waves is anticipated in the forthcoming period between 2023 and 2050. However, the highest wave heights are projected to be observed in the western region of the sea, in close proximity to the Azerbaijani coast and the Apsheron peninsula. Historical data indicates that this region is prone to intense and tumultuous winds, a consequence of its geographical location and orographic effect.

The mean wave height for future climate change projections at SSP5-8.5 in the Caspian Sea (Figure 4) is likely to be between 0.65 m and 1.2 m, with an average value of 0.99 m across the entire water area. The maximum wave height was found to be 5.79 m, with the smallest calculated maximum value being 1.73 m.

Under the SSP5-8.5 scenario, it is probable that the northeastern part of the sea will be subject to moderate to significant swell, while strong waves will spread in the eastern part.

The discrepancy between the maximum values under the two climate change scenarios is not substantial and exhibits no unidirectional trends.

The location of one of the state's strategic seabed areas in the Kazakh sector of the Caspian Sea provides a framework for ensuring the safety of offshore operations and preventing man-made emergencies [45]. It is imperative that the safety of offshore operations in the North Caspian Sea is guaranteed in accordance with the stipulations set forth in Chapter 19 of the Environmental Law of the Republic of Kazakhstan. This entails ensuring the normal spawning run of fish, the preservation of birds in nesting areas and the population of the Caspian Sea [46].

Sea surface condition is defined in points, contains characteristics of the appearance of the water surface created by wind of different strengths.

The sea state is characterized, among other things, by the degree of swell. The scale of the degree of swell, depending on the maximum height, is subdivided from weak to exceptional swell up to 11 m [47].

The calculation and prediction of waves on large bodies of water is of significant practical importance. It is of great importance to be aware of the dimensions and characteristics of waves in a given area of sea or coastline, as this knowledge is fundamental to the navigation of maritime vessels, the design and operation of ships, the design and construction of various hydraulic structures on the shelf and along the coastline, whose activity is dependent on the sea state [47]. Of the various characteristics of waves, maximum wave height is of particular significance, as high waves present the greatest risk to navigation and to hydraulic and shelf structures. The speed of navigation of ships at sea is significantly affected by the height of waves and their direction of propagation, which in turn affects the economic performance of ships.

For the Kazakhstan sector of the Caspian Sea, due to the very rare recurrence of very strong and exceptional waves, the wave degree scale was adjusted to the maximum possible calculated wave heights presented in Table 2.

Table 2

Wave Degree Scale of the Kazakhstan Sector of the Caspian Sea

Wave height, m	Degree of wave	Points	Colour code of the area
1.0...2.0	Moderate	I	
2.0...3.0	Significant	II	
3.0...4.0	Significant	III	
4.0...5.0	Strong	IV	
5.0...6.0	Strong	V	

In this regard, maps of zoning of the water area of the Kazakhstan sector of the Caspian Sea by the degree of excitement for the future for the period 2022...2050 were constructed under two climate change scenarios SSP1-2.6 and SSP5-8.5 (Figure 5).

The zoning maps were constructed on the basis of the "Atlas of zoning of seas and oceans for hydrometeorological support of maritime activities" [48], which includes the Caspian Sea zoning scheme, which includes the Caspian Sea zoning scheme. The boundary of the Kazakhstan part of the sea is drawn along the division points between the Caspian countries.

Due to shallow depths and sea level drop at present in the north-eastern part of the sea (area 4) it is conditionally agreeable that at this sea area the wind disturbance may not exceed 1...2 m and the degree of excitement will be moderate in I score.

The zoning map for the future (2022...2050) according to the SSP1-2.6 scenario showed that in districts 1...2, there is a significant wave of I, III and a strong wave of III, IV in districts 1...2. And in Area 3, significant swell of III is prevalent (Fig. 5 left).

In accordance with the projected climate change scenario SSP5-8.5, the following predictions can be made: in the first area, a strong swell of IV point and V point is to be expected; in the second area, a strong swell of IV point and a significant swell of III point are to be expected; in the third area, a significant swell of III point and a swell of III point are to be expected (Figure 5 right).

Table 3 presents the values of wave height variation by season. The least exposed to the influence of strong waves is spring, where, over the long-term retrospective period, the wave height in the Kazakhstan sector of the sea was between 1.1 m and 2.7 m. In the prospective period up to 2050, it did not exceed 2.05 m.

In summer, there is also significant swell, which did not exceed 1.7 m for 1959...2021, but projections for the future indicate that wave heights may reach a high wave level of 4 and 5.

The cold period of the year (autumn-winter) is the most susceptible to the influence of strong sea swell, mainly at 5 points, when the maximum wave height reached 3.2 m according to retrospective data. The results of climate change projection calculation showed that under the SSP1.25 scenario, the maximum wave height may reach 4.59 m, under SSP5-8.5 it may be 5.68 m and reach the upper limit of strong wave degree of 6 points.

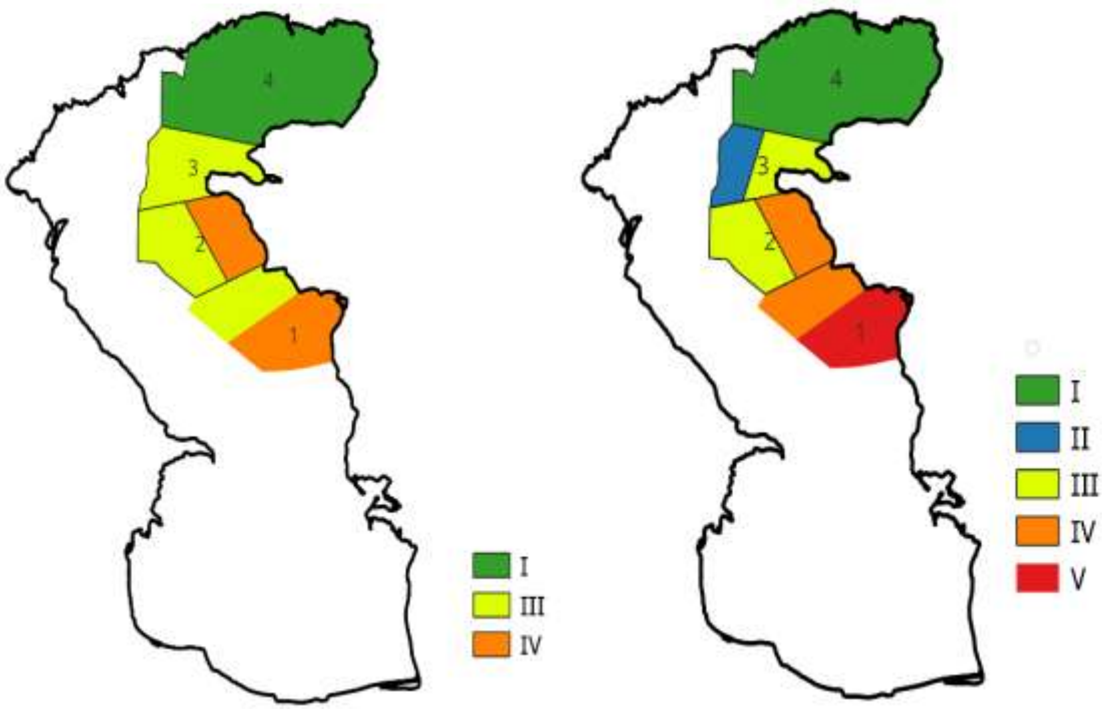

Figure 5. *Map of zoning of the Kazakh sector of the Caspian Sea by degree of wave according to climate change projections for 2023....2050 under scenarios SSP1-2.6 (left), SSP5-8.5 (right)*

4. CONCLUSION

At present, one of the main global threats to the security of the world's population is environmental problems, including the depletion of the ozone layer, global warming, the pollution of the world's oceans, the reduction of biological species, etc. [49]. In our region, the problem of the ecological state of the Caspian Sea, which washes the coasts of five countries, occupies a special place.

In order to mitigate the impact of man-made and natural emergencies on the coasts and waters of the Caspian Sea, it is imperative to consider the potential for significant wave height increases in the Middle Caspian Sea, which could reach 6 m by 2050. This necessitates the introduction of a special regime in areas prone to dangerous hydrometeorological phenomena, including tidal waves, strong waves, and storms. In the event of natural phenomena, the following measures should be taken:

1. Sites for the construction of structures at sea should be selected in accordance with the rules on the health protection of coastal waters.

2. When planning measures in the coastal zone, data on high and low water levels, as well as the maximum heights of rare future waves, should be obtained.

In order to prevent the effects of wave processes, it is necessary to construct protective dams in the areas of oil fields and settlements, as well as to reinforce and re-construct the existing dams.

DATA AVAILABILITY

The data used in this study were obtained by the authors from RSE Kazhydromet, Global Daily Downscaled Projections (NEX-GDDP-CMIP6) sources.

AUTHORS' CONTRIBUTIONS

Conceptualization – AY, SS; data curation – AY, GSh; formal analysis – AY, LB; мethodology – AY, SS; software – AY, LB, AK, GSh; supervision – SS, AY; В **v**isualization -AY, AK, NZh; writing – original draft – AY, SS; writing – review & editing – AY, SS, LB.

Table 3

Variation of estimated maximum wave heights in the Kazakhstan sector of the Caspian Sea

№	Area	Wave height, m		
		Retrospective	SSP1-2.6	SSP5-8.5
		YEARLY		
1	Kuryk	2.63...2.91	3.10... 4.34	3.76... 5.11
2	Aktau	2.63...3.19	3.10... 4.34	3.08... 4.43
3	Fort-Shevchenko	2.63...3.19	3.10... 4.34	2.40... 3.76
4	North-East Caspian	1.50... 3.19	1.86... 4.34	1.73... 3.76
		WINTER		
1	Kuryk	2.2...2.9	2.64... 4.59	3.67... 5.68
3	Aktau	2.5...3.2	2.64... 4.59	2.67... 4.67
3	Fort-Shevchenko	2.9...3.2	2.64... 3.62	2.67... 3.67
4	North-East Caspian	1.5... 2.5	1.66... 3.62	1.66 ... 4.67
		SPRING		
1	Kuryk	2.1...2.7	1.21... 2.05	1.10... 1.85
2	Aktau	2.4...2.7	1.21... 2.05	1.10... 1.85
3	Fort-Shevchenko	2.1...2.7	1.21... 2.05	1.10... 1.85
4	North-East Caspian	1.1... 2.4	0.8... 2.05	0.73... 1.85
		SUMMER		
1	Kuryk	1.4...1.6	2.63... 4.60	3.73... 4.76
2	Aktau	1.4...1.6	2.63... 3.62	2.69... 4.76
3	Fort-Shevchenko	1.4...1.6	2.63... 3.62	2.69... 3.73
4	North-East Caspian	0.8... 1.6	1.65... 3.62	1.66... 3.73
		AUTUMN		
1	Kuryk	2.0...2.5	2.64... 4.59	3.67... 5.68
2	Aktau	2.0...2.5	2.64... 3.62	2.67... 4.67
3	Fort-Shevchenko	2.3...2.5	2.64... 3.62	2.67... 3.67
4	North-East Caspian	1.1... 2.3	1.66... 3.62	1.66... 4.67

REFERENCES

1 Ardhuin F., Orfila A. (2018). Wind waves. New Frontiers in operational oceanography, Chapter 14, pp. 393-422 doi:10.17125/gov2018.ch14.

2 Casas-Prat M., Hemer M.A., Dodet G., Morimm J., Wang X., Mori N., Young I., Erikson L., Kamranzad B., Kumar P., Menen-dez M., Feng Y. (2024). Wind-wave climate changes and their impacts. Nature Reviews Earth and Environment 5, 23–42. doi: 10.1038/s43017-023-00502-0

3 Zou Q, Chen H. (2017). Wind and Current Effects on Extreme Wave Formation and Breaking. Journal of Physical Oceanography, 47, 1817–1841. doi: 10.1175/JPO-D-16-0183.1

4 Chen H., Zou Q. (2022). Geometry of Deep and Intermediate Water Breaking Waves Influenced by Wind Speed and Direction. Physics of Fluids, 087126, 13. doi: 10.1063/5.0101943.

5 Abuzyarov Z.K. (1981). Sea swell and its forecasting. Hydrometeoizdat, 162 p. http://elib.rshu.ru/files_books/pdf/img-417193526.pdf [in Russian]

6 Abuzyarov Z.K., Shamraev Y.I. (1974). Marine hydrological information and forecasts. Hydrometeoizdat, 218 p. https://korobkaknig.ru/gumanitar_nauka/nauki_o_zemle/morskie-gidrologicheskie-informacii-i-prognozy-35051.html [in Russian]

7 Abuzyarov Z.K., Dumanskaya I.O., Nesterov E.S. (2009). Operational oceanographic service, IG-SOCIN, 288 p. https://meteoinfo.ru/images/media/books-docs/ocean-monogr.pdf [in Russian]
8 Nesterov E.S. (2015). Extreme waves in oceans and seas, IG-SOCIN, 64 p. https://meteoinfo.ru/images/media/books-docs/special/nao-nesterov.pdf [in Russian]
9 Lopatukhin L.I. (2019). Wind-wave climate of the Caspian Sea. Meteorological Research, 47 (5), 89-97. doi:10.29006/1564-2291.JOR-2019.47(5).7 [in Russian]
10 Myslenkov S.A. (2017). Diagnosis and forecast of wind waves in the coastal zone of the Black Sea. Ph.D. Thesis, Moscow, Russia, 161 p. https://ipfran.ru/files/293/2017-myslenkov-diss.pdf [in Russian]
11 Pavlova A., Myslenkov S., Arkhipkin V., Surkova G. (2022). Storm surges and storm wind waves in the Caspian Sea in the present and future climate. Civil Engineering Journal. Vol 8, №11. p. 2353-2377. doi: 10.28991/CEJ-2022-08-11-01
12 Lebedev S.A. (2014). Satellite altimetry of the Caspian Sea. Ph.D. Thesis, Moscow, Russia, 350 p [in Russian]
13 Lebedev S., Kostianoy A. (2006). Satellite altimetry of the Caspian Sea. Current problems in remote sensing of the Earth from space. Vol.3, No.2, P. 113–120. http://www.iki.rssi.ru/earth/articles06/vol2-113-120.pdf
14 . Lavrova O.Yu., Kostyanoy A.G., Lebedev S.A., Mityagina M.I., Ginzburg A.I., Sheremet N.A. (2011). Integrated satellite monitoring of the Russian seas. IKI RAS, 2011, p. 480. [in Russian]
15 Yaitskaya N.A. (2017). Retrospective analysis of wind waves in the Caspian Sea in the second half of XX - early XXI centuries and the relationship with regional manifestations of climate change. Geographical Bulletin, 2(41), 57-70. doi 10.17072/2079-7877-2017-2-57-70 [in Russian]
16 Lopatukhin L.I., Yaitskaya N.A. (2019). Wave climate of the Caspian Sea. Wind input data for hydrodynamic modelling and some calculation results. Oceanology. 59 (1), 12-21. doi: 10.31857/S 0030-15745912-21
17 Lopatukhin L.I., Yaitskaya N.A. (2019). Data of reanalysis of wind fields over the Caspian Sea for calculation of the wind wave regime. Water Resources, 46 (6), 598-604. doi: 10.31857/S0321-0596466598-604
18 Myslenkov S.A., Arkhipkin V.S., Pavlova A.V., Dobrolyubov S.A. (2018). Wave climate of the Caspian Sea based on modelling data. Meteorology and Hydrology, 10, 60-70. https://istina.msu.ru/publications/article/156853005/
19 Dobrovolskiy A.D., Zalogin B.S. (1982). Seas of the USSR. Moscow: Moscow State University Publ., 192 p. [in Russian]
20 Yeltay A., Ivkina N.I., Klove Bjorn (2019). Wind influence on wave height in the Kazakhstan part of the Caspian Sea. Central Asian Journal of Water Resources Research, 5 (1-2), 82-94. doi: 10.29258/CAJWR/2019-R1.v5-1/58-70.eng
21 Yeltay A., Ivkina N., Narbayeva K. (2023). Verification of the results of the SWAN model for the water area near port Aktau. GEOMATE Journal, 25 (109), 77-84. doi: 10.21660/2023.109.m2305
22 Yeltay A. (2019). Monitoring of wind waves on the Kazakhstani coast of the Caspian Sea.Modern trends and prospects for the development of hydrometeorology in Russia, Irkutsk, June 5–7, 2019, pp. 172–178. [in Russian]
23 Mahmoudof D., Takami M. (2022). Numerical study of coastal wave profiles at the sandy beaches of Nowshahr (Southern Caspian Sea). Oceanologia Volume 64, Issue 3, July–September 2022. pp. 457-472.
24 Kamranzad D., Etemad-Shahidi A, Chegini V. (2016). Sustainability of wave energy resources in southern Caspian Sea. Energy Volume 97, 15 February 2016. pp. 549-559.
25 Strukov B.S., Zelenko A.A., Resnyansky Yu.D., Martynov S.L. (2012). Verification of the Wind Wave Forecasting System for the Black, Azov and Caspian Seas. Research Activities in Atmospheric and Oceanic Modelling. WCRP Informal Report № 5. CAS/JSC WGNE, Geneva: WMO, 2012. pp. 8.5–8.6. https://meteoinfo.ru/images/misc/sovet/zelenko/avtoreferat_zelenko.pdf
26 Strukov B.S., Zelenko A.A., Resnyansky Y.D., Martynov S.L. (2013). Wind wave characteristics forecasting system and the results of its testing for the Azov, Black and Caspian Seas. Information Collection № 40 New technologies, models and methods of hydrometeorological forecasts and the results of their operational tests, pp. 64-79 https://meteoinfo.ru/images/misc/sovet/zelenko/avtoreferat_zelenko.pdf
27 Bruneau N., Toumi R. (2016). A fully-coupled atmosphere-ocean-wave model of the Caspian Sea. Ocean Modeling. Vol. 107, pp. 97-111. doi: 10.1016/j.ocemod.2016.10.006
28 Rusu E., Onea F. (2013). Evaluation of the wind and wave energy along the Caspian Sea. Energy, Vol. 20137, pp. 1-14 doi: 10.1016/J.ENERGY.2012.11.044.
29 Ivkina N.I., Galaeva A.V. (2017). Forecasting of wind waves in the Caspian Sea using the SWAN model. Hydrometeorology and Ecology, 2 (85), 36-45. https://journal.kazhydromet.kz/index.php/kazgidro/article/view/1073
Mammadov R.M. (2014). Hydrometeorological atlas of the Caspian Sea. Baku [in Russian]
30 (2015). The electronic atlas of the Caspian Sea was developed with the support of the Russian Geographical Society. [Electronic resource]. URL: http://www.geogr.msu.ru/casp/ (date of access 10.10.2023)
31 Baidin S.S., Kosarev A.N. (1986). Caspian Sea: Hydrology and Hydrochemistry. Nauka, p. 261 [in Russian]
32 Kerimov A.A., Kosarev A.N., Terziev F.S. (1992). Project "Seas. Hydrometeorology and Hydrochemistry of the Seas". Volume VI Caspian Sea, Issue 1 Hydrometeorological conditions. Hydrometeoizdat, p. 358. https://www.geokniga.org/node/10916 [in Russian]
33 The Caspian Sea Lotiya, GUNiO (2016). p. 406. https://navysoft.ru
34 CASPCOM. Caspian Sea Level Information Bulletin No. 23 dated 13 May 2022 [Electronic resource]. URL: http://www.caspcom.com/files/CASPCOM%20Bulletin%20No.%2023_1.pdf. (date of access 15.06.2023)
35 Nesterov E.S. (2016). Water balance and Caspian Sea level fluctuations. Modelling and Forecasting, Triada. p. 378. http://www.caspianmonitoring.ru/wp-content/uploads/2018/08/8-Nesterov.pdf [in Russian]
36 Shiklomanov I.A. (1988). Land water resources research: results, problems, prospects, Hydrometeoizdat, p. 152. http://elib.rshu.ru/files_books/pdf/img-09056.pdf [in Russian]
37 Surface water resources of the USSR (1970). Issue 12, Lower Volga Region and Western Kazakhstan, Vol. 2. Ural-Embinsky district, Hydrometeoizdat, p. 510. http://www.cawater-info.net/library/ussr-water-resources.htm [in Russian]
38 Annual data on the regime of the Caspian Sea, Kazakhstan coast for 2020 (2022). RSE Kazhydromet, p. 61. https://www.kazhydromet.kz/en/kaspiyskoe-more/ezhegodnye-dannye-o-rezhime-kaspiyskogo-morya
39 GEBCO [Electronic resource]. URL: https://download.gebco.net/ (date of access 15.09.2021)
40 Global Daily Downscaled Projections (NEX-GDDP-CMIP6) [Electronic resource]. URL: https://www.nasa.gov/nex/gddp. (date of access 01.02.2023)
41 SWAN user manual (2024). Netherlands: Delft University of Technology, 146 p. https://swanmodel.sourceforge.io/download/zip/swanuse.pdf
42 SWAN. Scientific and technical documentation (2024). Netherlands: Delft University of Technology, 168 p. https://swanmodel.sourceforge.io/download/zip/swantech.pdf
43 Yeltay A., Narbaeva K. (2023). Wind disturbance in the Kazakhstan part of the Caspian Sea. International Conference of Students and Young Scientists “Farabi əlemi”, 3 p. [in Russian]

44 Law on Subsoil and Subsoil Use of the Republic of Kazakhstan dated 27 December 2017 No. 125-VI [Electronic resource]. URL: https://adilet.zan.kz/rus/docs/K1700000125. (date of access 15.06.2023) [in Russian]
45 Environmental Law of the Republic of Kazakhstan dated 2 January 2021 No. 400-VI. [Electronic resource]. URL: https://adilet.zan.kz/rus/docs/K2100000400 (date of access 15.06.2023) [in Russian]
46 Bogoslovsky B.B. (1980). Waves, currents and water masses of reservoirs. Leningrad, p. 58. [in Russian]
47 Atlas of zoning of seas and oceans for hydrometeorological support of maritime activities (2009). OJSC "Fabrika Offsetnoy Print", p. 43. http://mgmtmo.ru/edumat/normdoc/28_48.pdf [in Russian]
48 Drobot G.A., Kochetkova E.V. (2009). Ecological problems as a global threat to security, Bulletin of Moscow University, Issue.18, Sociology and Political Science, No.3, p. 61-73. [in Russian]

КАСПИЙ ТЕҢІЗІНІҢ ҚАЗАҚСТАНДЫҚ БӨЛІГІНДЕГІ БОЛАШАҚ ТОЛҚЫН БИІКТІГІНІҢ ДИНАМИКАСЫ

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ТҮЙІН СӨЗДЕР

Каспий теңізі;
толқын;
толқын биіктігі;
зоналау карталары

АБСТРАКТ

Каспий өңіріндегі мұнай-газ кен орындарын игеру, теңіздегі жыл бойы кеме қатынасының жүзеге асырылуы және биоалуантүрлілікті сақтау қажеттілігі Каспий теңізін кешенді зерттеуге, соның ішінде желдік толқындық құбылыстарды зерттеуге қызығушылықтың артуына себеп болды. Осы зерттеудің мақсаты – теңізде жел әсерінен толқындардың түзілу процесін зерттеу және олардың кеңістіктік пен уақыттық өзгерістерін болашақта сандық модельдеу негізінде бағалау. Бұл үшін спектралды-толқындық SWAN моделі қолданылды. 2050 жылға дейінгі толқын биіктігін болжау есептері NEX-GDDP-CMIP6 деректер жинағындағы климаттық модель нәтижелеріне сүйеніп, парниктік газдар шығарындыларының екі сценарийі бойынша жүргізілді. Есептеулер көрсеткендей, SSP1-2.6 сценарийі бойынша 2050 жылға дейін толқындардың ең жоғарғы биіктігі 1.1 м-ден 4.0 м-ге дейін өзгеруі мүмкін, ең жоғарғы мәндер 2023, 2029 және 2042 жылдары байқалады; SSP5-8.5 сценарийі бойынша ең жоғарғы толқын биіктігі 1.3 м-ден 4.1 м-ге дейін өзгеріп, ең жоғарғы мәндер 2029, 2033 және 2050 жылдары тіркелуі ықтимал. Қазақстандық бөлікте 2022...2050 жылдар аралығында айтарлықтай және күшті толқындардың пайда болуы мүмкін. 2050 жылға қарай Каспий теңізінің ортаңғы бөлігінде толқын биіктігі 6 метрге дейін жетуі ықтимал болғандықтан, мұнай кен орындары мен елді мекендер орналасқан аудандарда қорғаныс бөгеттерін салу, сондай-ақ бұрын салынғандарын нығайту мен қайта жаңғырту қажеттілігі туындайды.

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ДИНАМИКА ВЫСОТЫ ВОЛН В БУДУЩЕМ В КАЗАХСТАНСКОЙ ЧАСТИ КАСПИЙСКОГО МОРЯ

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КЛЮЧЕВЫЕ СЛОВА

Каспийское море;
волна;
высота волны;
карты зонирования

АБСТРАКТ

Разработка нефтяных и газовых месторождений в Каспийском регионе, круглогодичное судоходство в море и необходимость сохранения биоразнообразия привели к росту интереса к комплексным исследованиям Каспийского моря, в том числе к изучению ветровых возмущений. Целью данного исследования является изучение процесса образования ветровых волн в море и расчет их пространственных и временных изменений в будущем на основе численного моделирования с использованием спектрально-волновой модели SWAN. Расчеты прогноза высоты волн на период до 2050 года с использованием данных климатической модели из набора данных NEX-GDDP-CMIP6 для двух сценариев выбросов парниковых газов показали, что до 2050 года максимальная высота волн может варьироваться от 1.1 м до 4.0 м при SSP1-2.6 с максимальными значениями в 2023, 2029, 2042 годах; от 1.3 м до 4.1 м при SSP5-8.5 с максимальными значениями в 2029, 2033, 2050 годах. В казахстанской части моря в будущем (в период 2022…2050 гг.) возможны значительные и сильные волны. Поскольку к 2050 году высота волн в средней части Каспийского моря может достигать 6 м, необходимо построить защитные дамбы в районах нефтяных месторождений и населенных пунктов, а также укрепить и реконструировать ранее построенные.

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