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VERIFICATION OF THE RESULTS OF THE SWAN MODEL FOR THE WATER AREA NEAR PORT AKTAU

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ABSTRACT: The development of shipping and offshore drilling of new fields has led to an increase in the need for high-quality data on wave characteristics in the Caspian Sea. The purpose of the research is to verify the accuracy of the SWAN model in predicting wave characteristics in the water area near Port Aktau, in the Caspian Sea. The study also aims to provide high-quality data on wave processes at sea, which is important for the development of shipping and offshore drilling activities in the region. This paper analyzes the characteristics of wind and waves at the coastal station Aktau. Calculations of wave processes at sea were made using wave and wind data and numerical simulations using the SWAN model. The influence of the wind on the direction of the wave height is determined. The results show that the change in wave parameters depends on the speed and direction of the wind. An analysis showed that the waves directed to the southeast have the greatest frequency, and the wave height could reach 3.5 meters. In this paper, the modeling of wave processes, altimetry satellites, and their relationship with the SWAN wave model are investigated.

Keywords: Caspian Sea, Wind waves, SWAN, Kazakhstan part, Wave parameters

1. INTRODUCTION

Wind waves have great importance for shipping, construction, and operation of structures in the coastal zone and marine operations [1]. Numerical models are important tools for modeling wave conditions both in the open sea and in coastal areas, providing information on the wave parameters. The SWAN model is adapted and used to predict wind waves in various marine conditions. For example, the influence of storm events on the frequency of wave heights in the Black Sea was studied [2]. The sea state in the Baltic Sea basin was also modeled using the SWAN model to study wave climate variability over a long period of time spanning 41 years for periods with ice cover and ice-free [3]. The forecast of wind waves using the model in various parts of the sea showed good connections with the observed data at stations and buoys.

To study the wave climate and forecast waves in the Caspian Sea, there are various options for using wind-wave models [4-12]. The Caspian Sea is the world's largest drainage water body with a unique combination of the lake (lack of a natural connection with the sea) and sea (size, nature of processes, and origin) features. The Caspian Sea, together with the coastal territory and estuarine areas, has huge reserves of renewable and non-renewable natural resources.

The Caspian Sea is quite turbulent, especially in its middle and southern parts. In the northern part of the sea, the development of waves is limited by shallow water. In the middle part of the sea, the wave height can reach 6 m. The region of the Neftyanyye Kamni island, where wave height can reach 12 m [13]. The target area of this work is the coastal sector near the port of Aktau, located in the eastern part of the Middle Caspian.

The results of this study can also contribute to the development of shipping and offshore drilling in the Caspian Sea by providing high-quality data on wave characteristics. To ensure their stability and safety in various sea conditions, structures for offshore drilling, such as oil rigs and platforms, can be designed and optimized using the information acquired from the SWAN model. Also, in order to lessen the effects of waves on cargo and employee safety, shipping routes can be planned and vessel operations can be optimized using the data on wave characteristics. Hence, this study can contribute to the development of the marine industry in the Caspian Sea region by giving useful information on the behavior of waves and the influence of wind on wave characteristics.

2. RESEARCH SIGNIFICANCE

The research significance of this paper lies in its contribution to the understanding of wave characteristics in the Caspian Sea near the port of Aktau. By examining the influence of wind on wave height and direction, the paper sheds light on an important factor that affects the safety and efficiency of maritime activities in the region. The research has practical applications in the field of oceanography and can be used to improve the safety and efficiency of maritime operations in the Caspian Sea.

3. MATERIALS AND METHODS

The Caspian Sea is located in Eurasia between 47°07′ and 36°33′ N and 45°43′ and 54°03′ [14]. Of the 130 rivers flowing into the sea, the main rivers are the Volga, Ural, Terek, and Kura [15], which discharge about 276 km of water into the sea on average [16]. Winter air temperature ranges from -10ºC in the northeastern part to 8-12ºC in the south. In July-August, air temperature is over 24-26ºC and the maximum air temperature exceeds 40ºC [16]. The water temperature in winter can range from 0ºC 10-11ºC. The salinity of water in the area of the confluence of the Volga and Ural rivers is 0.1 ‰ and near the island of Kulaly 10-11‰ [14].

The study area covers the water area at the ports of Aktau and Kuryk. The Aktau port has 11 berths, 6 of which are oil, and 3 dry cargo. There are shipping routes from the port of Aktau to: Makhachkala, Baku, Astara, Anzali, and Amrahabad [17]. Kuryk port is located on the eastern coast of the Caspian Sea, south of Aktau port and is in a natural bay, which provides favorable weather conditions for its operation.

The wind regime near Aktau is characterized by the fact that in the mean annual section (1961-2019), the wind speed fluctuates within 4.1 m/s, and the maximum can reach 24 m/s. The regime of wind speeds is characterized by a gradual decrease from spring to summer [18]. When the wind blows over the surface of the water, it creates ripples that can grow into waves under certain conditions. The direction from which the wind is blowing determines the direction of the waves, and the speed of the wind affects the height of the waves. In the period 1961-2019, the prevailing wind direction in the mean annual section is the east. In the cold period of the year (autumn-winter), winds directed to the east are more often observed in the warm period (spring-summer) to the west (Table 1).

From the beginning of the observations at the coast in 1961 Aktau stations, 225 cases have been observed of excess wind speed of 15 m/s. The prevailing wind direction in stormy winds is the west (42%) and northwest (18.3%), which are destructive to the coast as they blow from the sea to land (Figure 1).

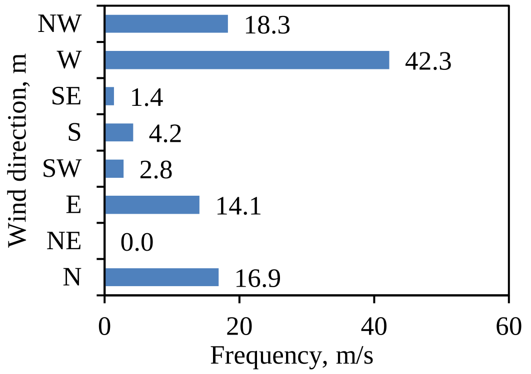


Fig.1 Repeatability of direction, wind excess 15 m/s

Of the total number of observed wave height data (about 28,000 cases), which are determined visually, 95.3 percent are at wave heights of up to 1 m. In 3.9 percent, cases with a height of up to 2 m, the remaining 0.7 percent is a wave when the height exceeds 2 m to a maximum 4.5 m. For further calculations, all these data were analyzed and the cases of observed maximum wave heights for each month were selected. As a result of this work, a catalog of significant waves was compiled for the stations of the Kazakhstani part of the Caspian Sea, which describes the height and direction of the waves, the date of their observation, the duration of this case in hours, as well as the wind characteristics for this wave (wind speed and direction).

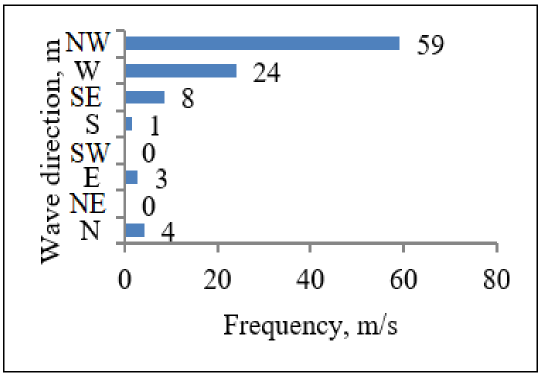


Fig.2 Repeatability of direction, wave excess 1.5 m

Table 1 Repeatability of wind directions by seasons

Season	Direction								
	N	NE	E	SE	S	SW	W	NW	Calm
Winter	13.9	13.1	33.4	18.9	2.7	1.7	6.0	7.6	2.7
Spring	11.2	9.8	16.9	13.4	8.3	6.6	17.8	11.6	4.3
Summer	15.5	10.3	8.8	5.8	6.5	6.9	25.1	14.7	6.3
Autumn	14.6	12.3	25.1	15.9	5.9	3.3	9.2	9.0	4.6
Year	13.8	11.4	21.0	13.5	5.9	4.7	14.6	10.8	4.5

Since 1980, about 70 cases of maximum wave have been observed in Aktau, and the north-west (59%) is the predominant direction of wave (Figure 2). The highest waves were recorded in the cold season (autumn-winter), when the maximum wave height ranged from 3 m in September to 4.5 m in December. The north-west is the predominant wave direction for the port of Aktau. Wind data affect the functioning of coastal structures, so it is important to study wave processes in the coastal waters using numerical models, in our case, the spectral-wave model of SWAN. SWAN (Simulating Waves Nearshore) is a third-generation spectral wave model that is used to obtain realistic estimates of wave parameters in coastal areas, lakes, and estuaries, taking into account given wind, bottom, and other conditions [19-21]. When describing the relationship between wind waves and wave formation conditions in the SWAN model, the solution of the wave field energy balance equation:

$$\frac{\Delta N}{\Delta t}+\frac{\Delta c_x N}{\Delta x}+\frac{\Delta c_y N}{\Delta y}+\frac{\Delta c_\sigma N}{\Delta \sigma}+\frac{\Delta c_\theta N}{\Delta \theta}=\frac{S_{tot}}{\sigma} \quad (1)$$

Where N is the specific spectral density; x, y – spatial coordinates; t – time; σ— wave frequency; θ – wave angle; c_x, c_y – propagation velocity in the spectral space (x, y); S_{tot} – is a source function that includes the following physical processes: wave generation due to wind energy, nonlinear wave energy transfer, wave reduction due to the formation of foam and splashes, friction against the bottom and crashing waves at a critical depth [11].

Significant wave height denoted as H_s defined as [22].

$$H_s = 4\sqrt{\iint E(\omega,\theta)d\omega d\theta}, \quad (2)$$

Where E (ω, θ) – variance density spectrum; ω – absolute radian frequency determined by the Doppler-shifted dispersion relation.

Wave direction, defined as:

$$\mathrm{DIR}=\frac{180}{\pi}\arctan\left[\frac{\int \sin\theta E(\sigma,\theta)d\sigma d\theta}{\int \cos\theta E(\sigma,\theta)d\sigma d\theta}\right] \quad (3)$$

Average absolute period, defined as:

$$\mathrm{PER}=2\pi\frac{\iint \omega^{p-1}E(\omega,\theta)d\omega d\theta}{\iint \omega^{p}E(\omega,\theta)d\omega d\theta} \quad (4)$$

The mean wavelength, defined as:

$$WLEN = 2\pi\left(\frac{\iint k^p E(\omega,\theta)d\omega d\theta}{\iint k^{p-1}E(\omega,\theta)d\omega d\theta}\right)^{-1} \quad (5)$$

Wave steepness computed as:

$$\mathrm{STEEPNESS}=\frac{H_s}{WLEN} \quad (6)$$

The Benjamin-Feir index or the steepness-over-randomness ratio, defined as:

$$\mathrm{BFI}=\sqrt{2\pi} * \mathrm{STEEPNESS} * \mathrm{QP} \quad (7)$$

Where, QP – peakedness of the wave spectrum.

The SWAN model was used in version 41.31 to simulate waves. The third-generation model is also in non-stationary mode using Cartesian coordinates. Bathymetry, flow, water level, bottom friction, vegetation, ice and wind should be provided by SWAN on the so-called input grids. It is best to make the input grid so large that it completely covers the computational grid [23]. Model calibration was performed in order to obtain maximum accuracy. When starting the model, the "GEN3" mode was used, in which the following parameters are used: KOMEN growth scheme (cds2 = 0.0, stpm = 0.1), three- and four-wave interaction (Quadrupl, Triad), collapse (Breaking constant, alfa = 1.0, gamma = 0.73), bottom friction (Friction Jonswap Constant cf = 0.067).

Model Input data: SWAN operates either in a Cartesian coordinate system or in a spherical coordinate system. In the spherical system that is used in this study, all geographic locations and orientations in the SWAN determine the geographic longitude and latitude. For calculations, a grid is created with a variable resolution for the water areas near Aktau in the SMS program (Surface-water Modeling System) (Figure 3). Unstructured meshes provide a much better view of complex areas, such as coastlines and areas around the islands. Using unstructured grids allows you to resolve the model area with relatively high accuracy but with a much smaller number of grid points than with conventional grids.

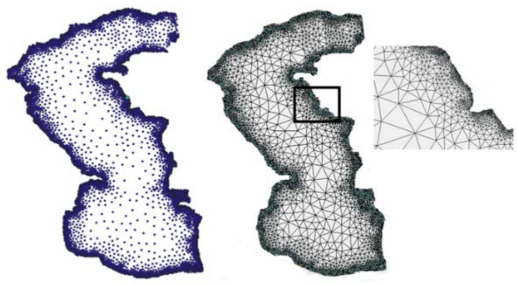


Fig.3 Regular and unstructured grid for water areas in Aktau

Wave growth depending on the wind is characterized by the equation:

$$\sin(\sigma,\theta)=A+BE(\sigma,\theta) \quad (8)$$

where, A – linear growth; BE – exponential growth. It should be noted that the SWAN model is determined by the wind speed at a height of 10 m above sea level.

The equation suggests that the sin of σ and θ is related to both linear growth (A) and exponential growth (BE multiplied by E(σ,θ)). This could represent a simplified representation of the growth or change in ocean waves, where the linear growth term (A) represents a constant or gradual change, and the exponential growth term (BE multiplied by E(σ,θ)) represents a potentially faster, exponential change in wave parameters.

The output parameters obtained from the integration of the wave spectrum can be provided throughout the computational grid or for specific locations: height and direction of the wave; wave period; wind speed and direction at selected points; average wavelength; average wave steepness; Benjamin-Feir index. To calibrate the model, the wind was used from the data of the European Center for Medium-Range Weather Forecasts (ECMWF) Ensemble Forecast Systems with a resolution of 0.25° by 0.25°. Wave parameters at Aktau were simulated for the period from January 1, 2018, to December 30, 2019, every 3 hours.

To calibrate and verify the results of the model, data for one point near the Aktau station were filtered out every 6 hours to compare them with the data of the observed data (Figure 4). The relationship between the wind speed observed at the station and from the European Center has a weak connection (correlation coefficient 0.56). Since the observation of the waves is carried out visually, it is necessary to compare the simulated values with satellite observations of the sea. Satellite altimeter data was distributed through NOAA, AVISO, EUMETSAT and PO.DAAC and the radar altimeter database system (RADS). For water areas near Aktau, altimetry data were analyzed from the RADS database. RADS currently allows users to retrieve data from several current and past satellite altimeter missions [24, 25].

Satellites Cryosat 2, Jason 3, Sentinel 3 A made observations of the object of study. On average, each satellite made observations 3 times a month, that is, 3 different passages in the water area, for 2018-2019 years, satellite data coverage of 197 days. To analyze wind speed data, data from altimeter satellites and ECMWF were compared (Figure 5). The statistical parameters presented above were considered to evaluate the accuracy of wind speed. Values are presented in Table 2 [26-28].

4. RESULTS AND DISCUSSION

The analysis of the observed data showed that the north-west, which blows from the sea to the land, is the predominant wave direction for the port of Aktau. For Aktau, the wind has the greatest repeatability at a speed of 2-3 m/s directed to the northeast. But according to various guards, the prevailing direction is diverse, for speeds from 1-3 m/s northeast, 4-5 m/s east, 6-7 m/s east southeast, 8-11 m/s southeast, and for speeds of 12-13 m/s the direction to the north-west. In the studied region of the Caspian Sea, seasonal differences in the regime of wind direction are quite clearly manifested, which indicates a monsoon component.

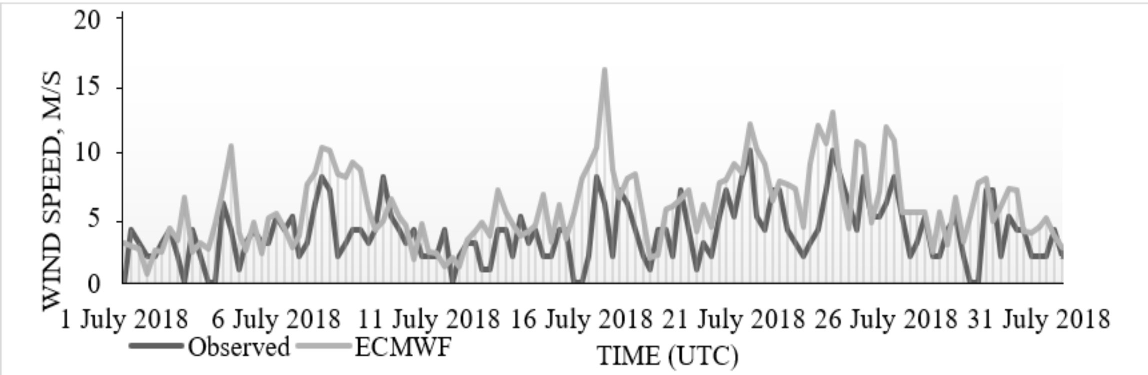


Fig.4 Time series plot of wind speed for Aktau station July 2018.

Table 2 Statistical parameters computed for wind speed.

Wind speed data	Average	Maximum	Minimum	Correlation	RMSE	Mean Bias error	Standard deviation
ECMWF	6.5	12.9	1.1	0.77	2.20	0.62	3.17
Data from altimeter satellites	5.9	13.0	1.2				

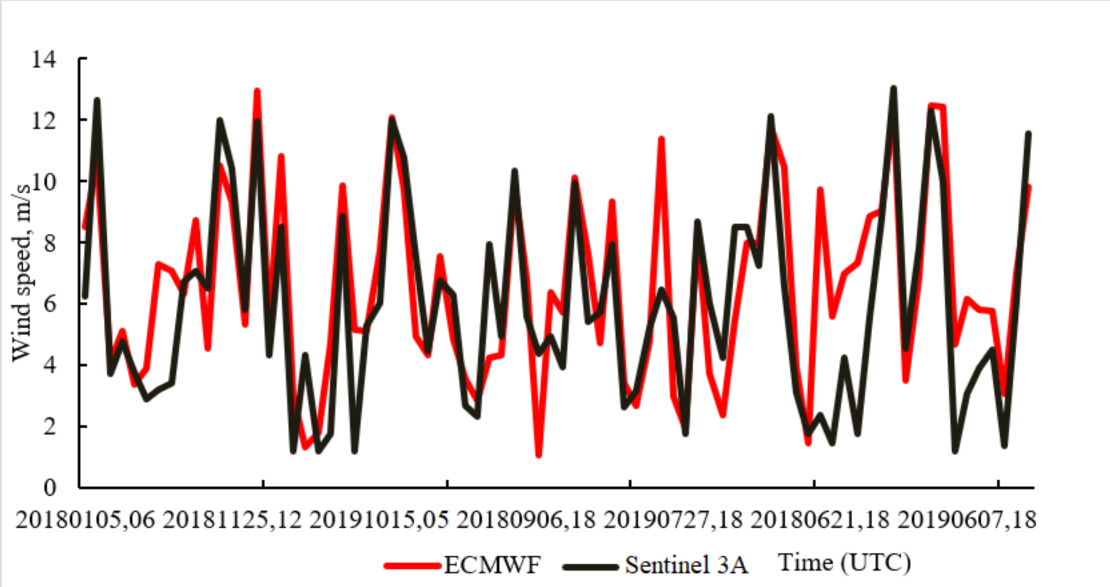


Fig.5 Time series of wind speed according to ECMWF and Sentinel 3A data

An analysis was made of a two-year period of wind turbulence in the Caspian Sea. The third-generation SWAN wave model was adapted for the area covering the water area near the port of Aktau with a resolution of 0.125. To perform the wave model, 3-hour intervals were selected. Thus, the total number of data sets is 2800. The wind speed observed at Aktau station and ECMWF data have similar changes throughout the year, but the wind speed is on average, 1-1.5 times less at the station than at the determined ECMWF. This can be explained by the location of the observational network on the seashore.

Waves with a height of 0.25-0.75 m and directions to the northeast, east and southeast occurred more often during 2018-2019, in a total of 96.4%. An unstructured grid with a step of 0.125° was used. A field of wave characteristics was obtained for every 3 hours from 2018-2019: significant wave height, the average direction of wave propagation, average wave period, average wavelength, average wave steepness, and Benjamin-Feir index. The wind field at an altitude of 10 m above sea level, according to the ECMWF is used as a stimulating effect. The wind field represents the wind components U and V with a time step of 6 hours and a spatial resolution of 0.25°.

An analysis of the simulated values of the wave parameters showed that the maximum wave height exceeding 3 m was recorded in 6 cases in 2018-2019, with the wave direction to the northwest and southeast. On December 14, 2018, at 06.00 at a wind speed of 15 m/s, the wave height reached 4.63 m, the wave period was 7.99 seconds, with an average wavelength of 65.37 m, and with an average wave slope of 0.05 (Figure 6).

A comparison of the data for calculating the wave periods was not performed. According to the model, the average wave period is 3.32 s, and the maximum value is 25.71 s. Since the highest values of wave height were in 2018, an analysis of seasonal changes in wave parameters was made (Table 3). In December, the average value of wave height was 1.11 m, and the maximum was 3.79 m, while in February, they averaged 0.93 m, a maximum of 2.25 m. In the summer of 2018, significant wave heights reached an average of 0.62 m and a maximum of 1.95 m, while the average period was 3.00 seconds.

Wave height, according to simulated values for 2018-2019, is in the range of 0.25 to 0.75 m (46.1 %). The model gives better results about the wave height since the values of the wave height depend on the characteristics of the wind.

Table 3 Parameters of excitement by the seasons of the year

Wave parameters		Winter	Spring	Summer	Autumn
Average	SWH, m	1.01	0.80	0.62	0.91
	Wave period, [s]	3.64	3.35	3.00	3.50
	Wave length, [m]	19.00	15.61	12.11	17.26
	Steepness	0.06	0.05	0.05	0.05
Maximum	SWH, [m]	3.79	2.41	1.95	2.63
	Wave period, [s]	6.89	6.01	5.07	6.42
	Wave length, [m]	65.37	46.79	34.68	59.91
	Steepness	0.09	0.09	0.09	0.08

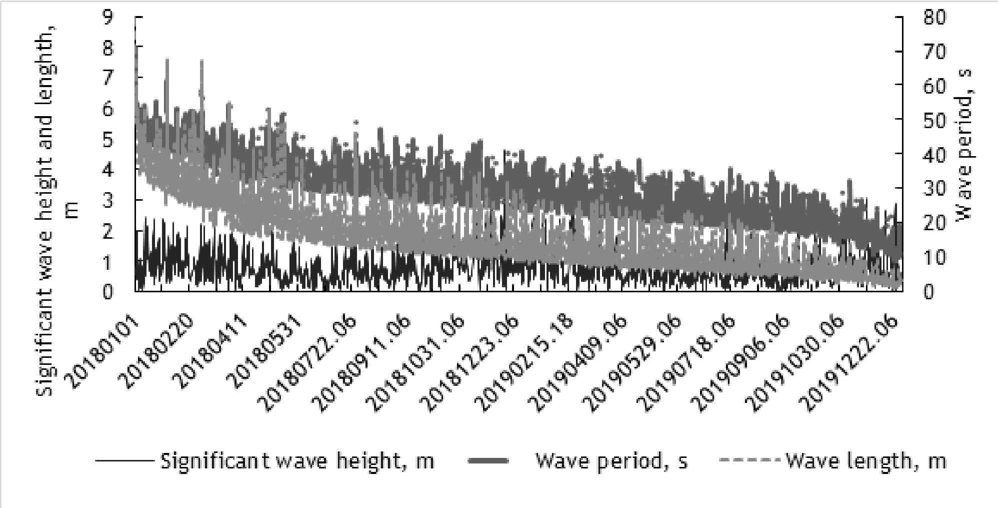


Fig.6 Time series plot of simulated wave parameters during 2018-2019 for Aktau station

A comparison was made of the prevailing wind direction for 2018-2019 according to the observed and simulated values (Figure 7), which showed that the southeast and the northwest in both cases are the predominant wave direction. For comparison, the simulation results, the values of significant wave height were obtained with altimeters. Figure 8 show the graphs of changes in the wave height of the simulated and altimetric. On average, modeled values are similar during a given altimeters.

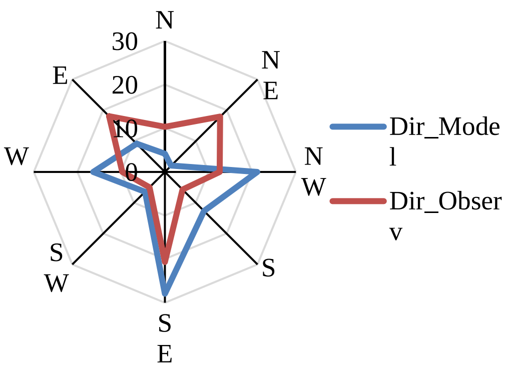


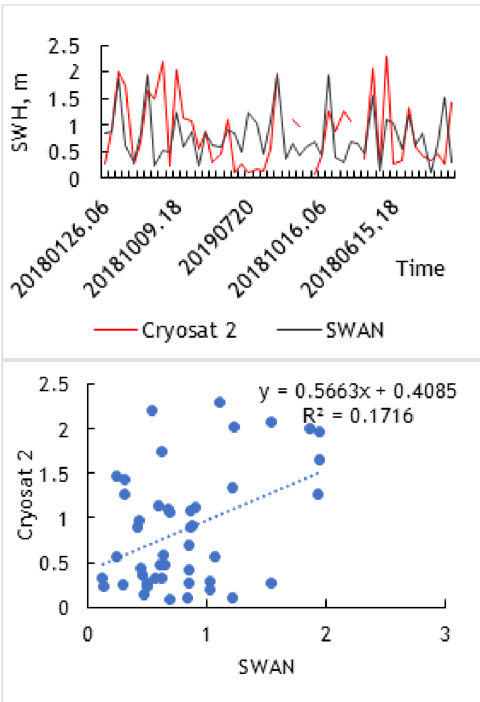
Fig.7 Rose of the wave direction for the observed and modeled wave values in Aktau.

Table 4 Model calibration analysis at Aktau station

Data	Mean	Standard deviation	RMSE	R	Mean BIAS error
Cryosat	0.87	0.57	0.63	0.41	-0.057
Jason 3	0.78	0.54	0.45	0.66	-0.015
Sentinel 3	0.77	0.65	0.44	0.80	0.061

Table 4 shows the values of the analysis of the calibration of the model and satellites of the altimeters. Which showed that the relationship of the simulated wave values has a good correlation with the data from the Sentinel 3 satellite.

The SWAN wave model significantly benefits from the use of altimetry satellites. The SWAN model's integration with altimetry satellites offers the chance to calibrate and assess the precision of the generated wave data. Wave heights and times can be precisely measured by altimetry satellites and compared to the simulated data from the SWAN model. This enables the SWAN model to be modified in order to improve its precision and dependability. The growth of offshore drilling and shipping can benefit greatly from the incorporation of altimetry satellite data into the SWAN model, which can also provide a more thorough understanding of wave characteristics in the Caspian Sea.



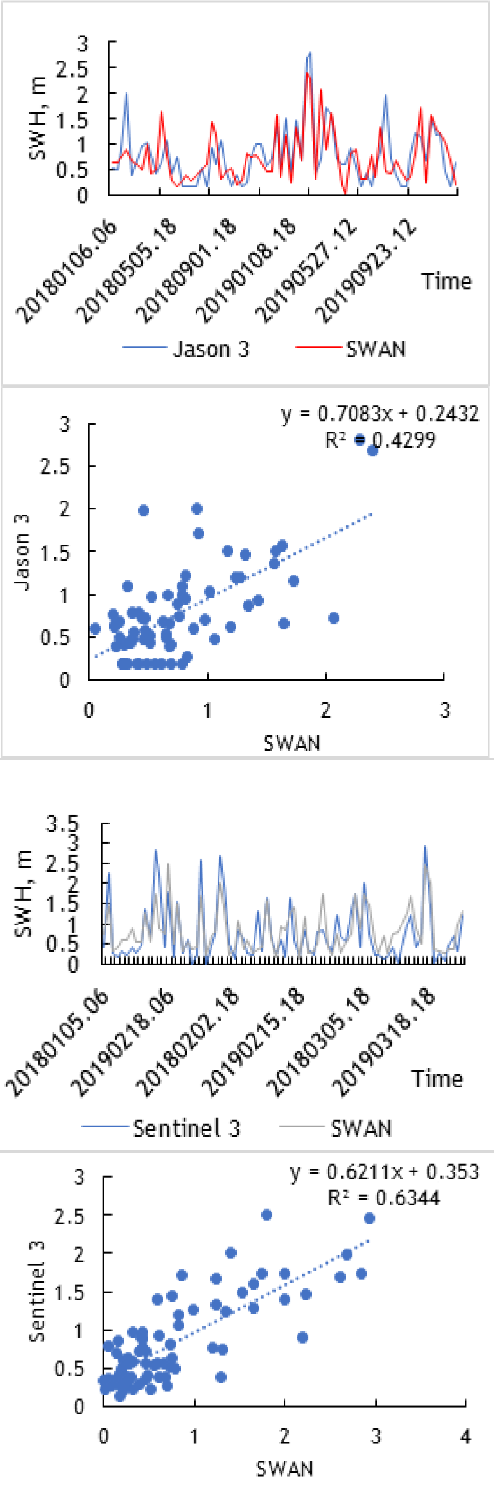


Fig. 8 Graph of the wave height change according to satellite altimetry data and simulated values

5. CONCLUSION

The work explored the area near the port of Aktau on the Caspian Sea and changes in hydrometeorological parameters, such as wind speed, direction, sea waves and their characteristics, over a long period. To determine wave processes, the SWAN spectral-wave model was adapted for this water area, and the wave parameters that can be modeled are described. The input parameters are the triangulation grid, wind (meridional and zonal), and the coordinates of the point for which the modeled values of the output parameters are needed. The output characteristics of the model are different; in this work, we used the height and direction of waves, period and wavelength, wind speed and direction, and average wave steepness.

For the calibration, data from ECMWF were used. Simulated waves were compared with altimeter satellites. The results showed that the relationship of the simulated wave values has the most effective correlation with the data from the Sentinel 3 satellite. Wind wave research is especially important for offshore operations. The study of waves in the open sea area is complicated by fluctuations in sea level and frequent gale winds. In this paper, the modeling of wave processes, altimetry satellites, and their relationship with the SWAN wave model are investigated.

All the objectives of the conducted research have been achieved. The accuracy of the SWAN model in predicting wave characteristics in the water area near Port Aktau, in the Caspian Sea, was verified; the high-quality data on wave processes at sea, which is important for the development of shipping and offshore drilling activities in the region, were provided.

There are several opportunities for more investigation into the matter of confirming the outcomes of the SWAN model for the water area surrounding Port Aktau. Increasing the study's time span and concentrating on examining the seasonal and interannual variations of wave properties are two prospective research directions. This could offer useful information for organizing offshore operations and raising Caspian Sea safety. Investigating how other environmental elements, such as water temperature, salinity, and ocean currents, affect wave characteristics is another possible field of study. This might contribute to increasing the precision of wave models and offering more thorough data for offshore engineering and design.

6. REFERENCES

[1] Divinsky B.V., Fomin V.V., Kosyan R.D., and Ratner Y.D., Extreme wind waves in the Black Sea, Oceanologia, Vol. 62, 2020, pp. 23-30.

[2] Medvedeva A.Yu., Arkhipkin V.S., Myslenkov S.A., and Zilitinkevich S.S., The wave climate of the Baltic sea based on the results obtained with the use of the swan spectral model, Moscow University Bulletin, 5, 2014,pp. 12-22.

[3] Björkqvist J.-V., Ingvar L., Alari V., van Vledder G.Ph., Hulst S., and Pettersson H., Comparing a 41-year model hindcast with decades of wave measurements from the Baltic Sea, Ocean Engineering, Vol. 152, 2018, pp. 57-71.
[4] Zamani A., Azimian A., Heemink A., and Solomatine D., Non-linear wave data assimilation with an ANN-type wind-wave model and Ensemble Kalman Filter (EnKF), Applied Mathematical Modeling, Vol. 34, 2010, pp. 1984-1999.
[5] Amirinia G., Kamranzad B., and Alafi S., Wina and wave energy potential in southern Caspian Sea using uncertainty analysis, Energy, Vol. 120, 2017, pp. 332-345.
[6] Golshani A., Nakhaee A., Taebi S., Chegini V., and Alaee M.J., Wave Hindcast study of the Caspian Sea, Journal of Marine Engineering, Vol. 3, 2005, p. 15.
[7] Allahdadi M.N., Chegini V., Fotouhi N., and Golshani A., Wave modelling and hindcast of the Caspian Sea, Conference paper, ICOPMAS, Vol. 1, 2004, pp. 1-10.
[8] Bruneau N., and Toumi R., A fully-coupled atmosphere-ocean-wave model of the Caspian Sea, Ocean Modeling, Vol. 107, 2016, pp. 97-111.
[9] Nicholls J.F., Modeling of the Caspian Sea, Space and Atmospheric physics group, London, 2013, pp. 1-217.
[10] Lopatukhin L.I., and Yaitskaya N.A., Wave climate of the Caspian Sea, Wind input data for hydrodynamic modeling and some calculation results, Oceanology, Vol. 59, Issue 1, 2019, pp. 12-21.
[11] Rusu E., and Onea F., Evaluation of the wind and wave energy along the Caspian Sea, Energy, Vol. 50, 2013, pp. 1-14.
[12] Ivkina N.I., and Galaeva A.V., Forecasting windwave on the Caspian Sea using the SWAN model, Hydrometeorology and Ecology, Vol. 2, Issue 85, 2017, pp. 36-45.
[13] Pilot of the Caspian Sea, Publishing house GUN and O, St. Petersburg, 2016, pp. 1-387.
[14] Terziev F.S., Kosarev A.N., and Kerimov A.A., Hydrometeorology and hydrochemistry of the seas, Drometeoizdat, Sankt-Peterburg, 1992., pp. 1-241
[15] Ivkina N.I., Change of water inflow to the Caspian Sea as a result of anthropogenous influence and climate change on the example of ZHayik (Ural) river, Hydrometeorology and Ecology, Vol. 3, Issue 82, 2016, pp. 50-55.
[16] Kosarev A.N., Physico-geographical conditions of the Caspian, The Caspian Sea environment, Springer, Berlin, 2005, pp. 5-31.
[17] JSC NC Aktau Sea Commercial Port, 2021, Retrieved from http://www.portaktau.kz/ru/.
[18] Yeltay A., Features of the wind regime in the Kazakh part of the Caspian Sea, Hydrometeorology and Ecology, Vol. 1, Issue 92, 2019, pp. 63-72.
[19] Booij N., Ris R.K., and Holthuijsen E.H., A third-generation wave model for coastal regions: Model description and validation, Geophysical Research, Vol. 104, Issue 4, 1999, pp. 7649-7666.
[20] SWAN Technical Documentation, SWAN Cycle III version 41.31, Netherlands: University of Technology, 2019.
[21] Divinsky B., and Kosyan R.D., Parameters of wind seas and swell in the Black Sea based on numerical modeling, Oceanologia, Vol. 60, 2018, pp. 277-287.
[22] SWAN User manual, SWAN Cycle III version 41.31, Netherlands: University of Technology, 2019.
[23] SWAN home page, 2019, Retrieved from http://swanmodel.sourceforge.net/.
[24] Radar Altimeter Database System, 2020, Retrieved from http://rads.tudelft.nl/rads/rads.shtml.
[25] Muliati Y., Tawekal R.L., Wurjanto A., Kelvin J., and Pranowo W.S., Application of swan model for hindcasting wave height in Jepara coastal waters, North Java, Indonesia, GEOMATE Journal, Vol. 15, No. 48, 2018, pp. 114-120.
[26] Yeltay A., Ivkina N., and Klove B., Influence of wind on wave heights in the Kazakh Caspian Sea, Central Asian Journal of Water Research, Vol. 5, Issue 1, 2019, pp. 58-70.
[27] Koshinskiy S.D., Operating characteristics of strong winds in the seas of the Soviet Union, Part 1, Caspian Sea, Leningrad: Gidrometeoizdat, 1975, pp. 1-412.
[28] Muliati Y., Tawekal R.L., Wurjanto A., Kelvin J., and Pranowo W.S., Wind wave modeling in Natuna sea: A comparison among swan, Seafine, and era-interim, GEOMATE Journal, Vol. 16, No. 54, 2021, pp. 176-184.