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Influence of wind on wave heights in the Kazakh Caspian Sea

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Abstract
With the development of shipping in the Caspian Sea, the need for high-quality data on wave characteristics has increased. In the present work, the analysis of maximum wave height at coastal stations in Kazakhstan was carried out using wave and wind data and numerical modeling with the SWAN model. The influence of stationary wind and its direction on the wave height was determined. The results show that the changes in the parameters of the wind wave depend on the wind speed and direction. At wind speeds below 10 m/s, the predicted wave height can reach 3 m in the Middle Caspian basin. In the Northern Caspian basin, where the depths are shallow, the waves do not exceed 2 m. The study output produced the first wind zoning map for the Kazakh part of the Caspian Sea.

Keywords: sea, stationary wind, wave parameters, SWAN model, zoning maps.

Paper type: Research paper

1. Introduction

The Caspian Sea lies in a strategic position at the crossroads of international transport between Europe and Asia. The vast natural resources have made the Caspian Sea into a dynamically developing industrial, transport and shipping center. To prevent accidents at sea, increasing the traffic on the Caspian Sea requires accurate forecasts on its currents and waves. An oil tanker accident in 2011 when the tanker "Grigory Bugrov" suffered a disaster in the Caspian Sea on October 13. The vessel got a hole and ran aground 50 kilometers from Tyuleniy Island according to regional internet media (Ionov 2011). He went from Turkmenistan to Astrakhan with six thousand tons of fuel oil on board.

Past research on wind waves studies shows that significant waves in the sea occur due to winds from west to north (Ivkina & Stroeva 2005; Ivkina et.al 2006). In the second half of the 19th and the beginning of the 20th centuries, the amplitude of the wave parameters from north to south increased and it was shown that the depth of the sea plays an important role in the formation of waves in the shallow northern part of Caspian (Yaitskaya 2017). However, a small number of the monitoring network of hydrometeorological characteristics leads to a lack of sufficient information about the region. Also, wave characteristics are not observed in the open part of the sea, which complicates the analysis and forecast of wave parameters.

The objective of the study was to improve the knowledge of waves in the Caspian Sea. In the presented work, the authors use data from the Kazakh Caspian Sea stations and calculations using the SWAN numerical model to show wind and wave characteristics (wave height and period) in the sea. Of particular importance and relevance were studies of the wave mode, which were determined mainly by the distribution of the speed and direction of the prevailing winds. This allowed tacking of the interannual variability of the waves and the long-term distribution of wave heights. Therefore, along with the study of wave conditions wind regimes were analyzed.

2. Materials and methods

2.1. Caspian Sea study area

The Caspian Sea inland water body with borders to the Russian Federation, Republic of Kazakhstan, Republic of Turkmenistan, Islamic Republic of Iran and the Republic of Azerbaijan. The water body consists of three major basins with different depths. The sea is important for fisheries, ecology, recreation, and transport. The Northernmost basin is shallow and ice covered in the winter. The southern basin lies in a temperate climate and is ice-free and deep.

The Caspian Sea major traffic routes are from Aktau to Baku and Mahachkala (Figure 1). The main ports in Kazakhstan are "Aktau Sea Trade Port" and "Port Kuryk". These are multifunctional terminals that ensure the transportation of goods throughout the year, continuously from east to west, from north to south and in the opposite direction. Their location at the intersection of the largest transport corridors of the region is of strategic importance in the development of Kazakhstan (portaktau.kz, portkuryk.kz).

2.2. Caspian Sea climate and winds

The climate over the Caspian Sea and the territories around it is influenced by atmospheric circulation over the Eurasian continent. In winter, cold arctic weather conditions form in the northern Caspian Sea basin. At this time, simultaneously with the mountainous territory of Iran, air flows into the sea, and the collision of these two high-pressure air flows in the middle of the sea creates a cyclonic air period. In addition, cyclones of the Black and Mediterranean Seas also affect the Caspian. In the spring, the Siberian anticyclone and the cyclone of the Mediterranean Sea advance into the eastern and northeastern directions, as a result, the synoptic processes and air currents often change. In summer, temperature contrasts are

smoothed, circulation processes in the lower and upper layers of the atmosphere weaken. During this period, the Azores maximum influences the synoptic processes over the Caspian. By mid-autumn, the influence of the Azores high begins to weaken, continental air flows from the east, and western interference with the atmosphere is intensifying (Hydrometeorology and hydrochemistry of the seas 1992; Arpe et.al 2019).

Maximum winds occur after the development of the Siberian anticyclone when the conditions the largest gradient of pressure occur in the south-eastern direction. In the summer, the frequency of the westerly winds increases, which is associated with the frequent passage of cyclones from the Atlantic through Western Kazakhstan and the south of the Urals (Hydrometeorology and hydrochemistry of the seas 1992).

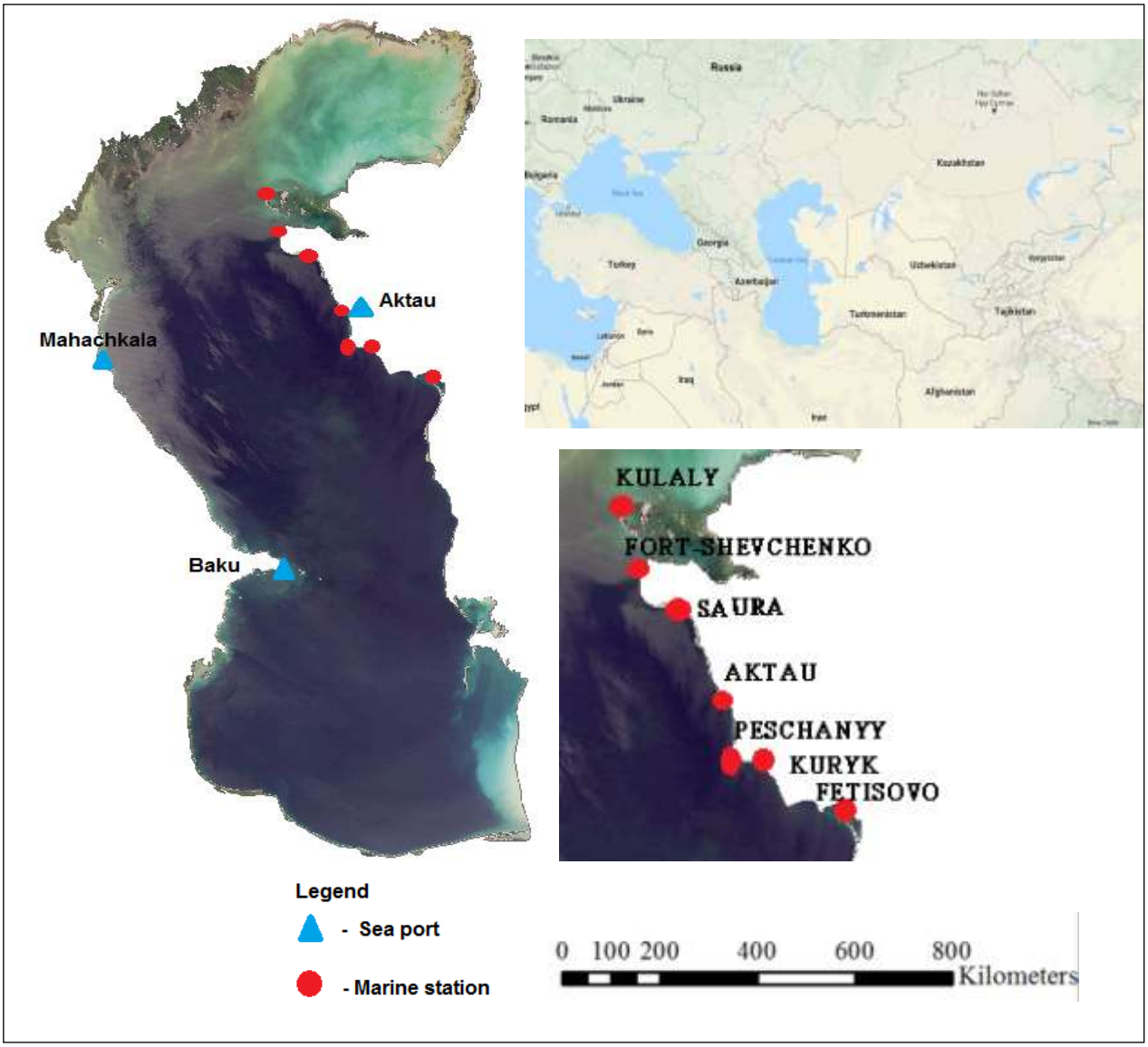


Figure 1. The Caspian Sea ports and the sea measurement stations in Kazakhstan (MODIS space image).

2.3. Wind and wave monitoring in the Kazakh Caspian Sea

In the coastal waters of the Caspian Sea, observations relating to Kazakhstan are carried out at 10 sea stations: Igolkinskaya Bank, Zhanbay, Peshnoy, Kulaly Island, Fort-Shevchenko, Aktau, Peschanyy, Fetisovo, Saura, Kuryk. Measurements for wave characteristics are carried out in 7 of them, which are shown in Figure 1. At these hydrometeorological sea stations, observations are made of wind characteristics, such as wind speed and direction, wave height and direction, water and air temperature, water level, sea salinity. The data on wave height and direction was used from stations Aktau, Fort-Shevchenko, Kulaly Island. The data used was observed at times 00, 06, 12, 18 h, GMT. The stations are located as shown in Figure 1. Data has been collected since 1980-2017 (Table I).

The analysis of available observational data on the direction and speed of wind obtained at Aktau, Kulaly Island, Fort-Shevchenko stations for the period from 1980-2017 was carried out. The analysis of observations over the direction and speed of the wind was carried out on a four-line analysis of wind on the 10-meter horizon of these stations. Wind data (speed and direction) are complete; there are only a few omissions of the observation time, but in general, they are suitable for statistical processing.

2.4. SWAN modelling

Wave modeling by stationary wind values in different directions was made according to the SWAN (Simulating Waves Nearshore) model. The model was developed at the Faculty of Civil Engineering and Earth Sciences of the Delft University of Technology, the Netherlands. We used version 41.01A (SWAN Technical Documentation, 2007). Meanings of significant wave height denoted as H_s in meters and defined as

$$H_s = 4\sqrt{\iint E(\omega,\theta)d\omega d\theta} \quad (1)$$

Where, $E(\omega,\theta)$ is the variance density spectrum and ω is the absolute radian frequency determined by the Doppler shifted dispersion relation. However, for ease of computation, H_s can be determined as follows

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

This model was adapted to the conditions of the Kazakhstan part of the Caspian Sea by Ivkina and Galaeva (Ivkina et al. 2016; Ivkina et al. 2017).

The input parameters for the model are data on the wind regime (speed, direction), bathymetry and an irregular triangulation grid of the Caspian Sea, and coordinates of points on which it is necessary to make a calculation.

The modeling steps to simulate waves caused by stationary wind conditions are:

- prepare input parameters;
- prepare the code for the program that starts the simulation process;
- obtain simulation results and visualize these in ArcGIS.

3. Results and discussion

3.1. Wind characteristics

The average annual wind speeds in the Kazakh region of the Caspian Sea is 4–5 m/s. The annual winds prevail from the easterly direction in the winter months. The maximum wind speed varies from 22-28 m/s and is typically observed in the cold season, from October to March. The lowest wind speeds are observed in the summer months, from June to August, is 2.4 and 3.8 m/s in the North and 4.7 and 5.2 m/s in the South (Figures 2-3).

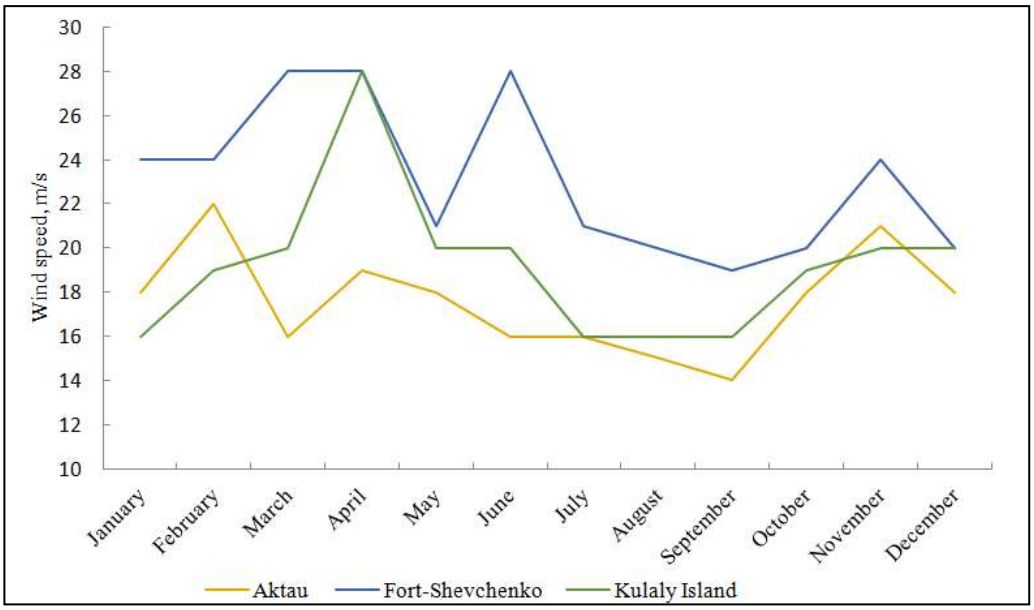


Figure 2. Monthly maximum wind speed in Aktau from 1980 to 2017, Fort-Shevchenko from 1993 to 2017, and Kulaly Island from 2001 to 2017.

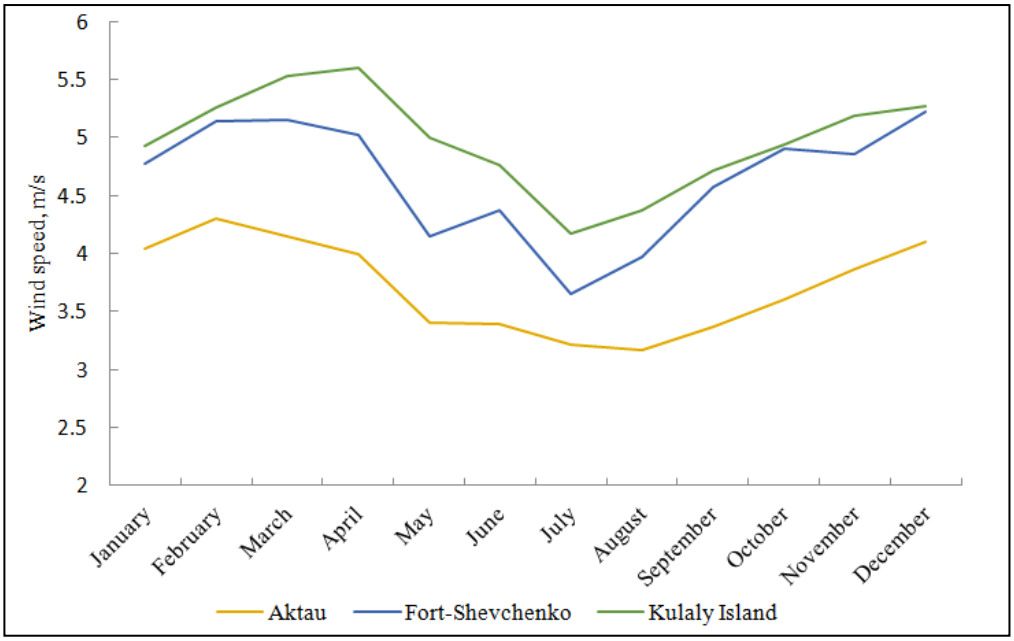


Figure 3. Monthly average wind speed in Aktau from 1980 to 2017, Fort-Shevchenko from 1993 to 2017, and Kulaly Island from 2001 to 2017.

The highest wave height in the Kazakhstan sector of the Northern Caspian can reach 3 m near Kulaly Island. Significant and strong waves, as a rule, cause westerly and northerly winds, and even moderate winds that have a steady direction for more than 24 hours can cause high waves.

Table I. Coastal stations, measurement periods, average and maximum wind speeds and wave.

Station	Period, years	Average wind speed, m/s	Maximum wind speed, m/s	Average wave height, m	Maximum wave height, m
Aktau	1980-2017	3,7	22	0,20	4,5
Fort-Shevchenko	1993-2017	4,7	28	0,33	2,5
Kulaly Island	2001-2017	5	24	0,49	3

3.2. Wave height analysis

The analysis of the frequency of wave height at coast stations shows the waves below 0.5 m to be the most common (Table II). The average wave height is for Aktau 0.20 m, Fort-Shevchenko 0.33 m and Kulaly Island 0.49 m. Analysis of the frequency of waves of different heights at the stations showed that for all the years of visual measurement of the wave height,

the maximum reached 4.5 meters in the area of the city of Aktau. It can be concluded that the formation of waves with a height of more than 4 m is possible but very rare.

Table II. Wave height repeatability by station.

Station	Wave height, m								
	<0.5	0.5 -1	1 – 1.5	1.5 - 2	2 – 2.5	2.5 - 3	3 – 3.5	3.5 - 4	4 – 4.5
Aktau	24392 (88,8%)	17426 (6,3%)	890 (3,2%)	253 (0,9%)	138 (0,5%)	44 (0,2%)	18 (0,1%)	4 (0,01%)	1 (0,004%)
Fort-Shevchenko	14522 (62,9%)	7589 (32,9%)	778 (3,4%)	170 (0,7%)	13 (0,1%)	1(0,004%)	-	-	-
Kulaly Island	6478 (32,9%)	10447 (53,0%)	2205 (11,2%)	396 (2,0%)	164 (0,8%)	8(0,04%)	1 (0,01%)	-	-

The stations have different wind and wave characteristics. In the Fort-Shevchenko region, considerable winds are observed throughout the year. High waves are common for winter (January-February), spring (March-April) and autumn (October-November) periods. In the Aktau area, wave processes are more developed, waves with a height of more than 1.5 m are recorded in each month. High waves were observed throughout the year, but the most intense wave processes, as well as for the area of Fort-Shevchenko, are developed in winter (December-February), spring (March-April) and autumn periods (October-November). At Kulaly Island, maximum excitement with a height of more than 2 m is observed throughout the whole year, but in November and spring they are expressed intensively (Figure 4).

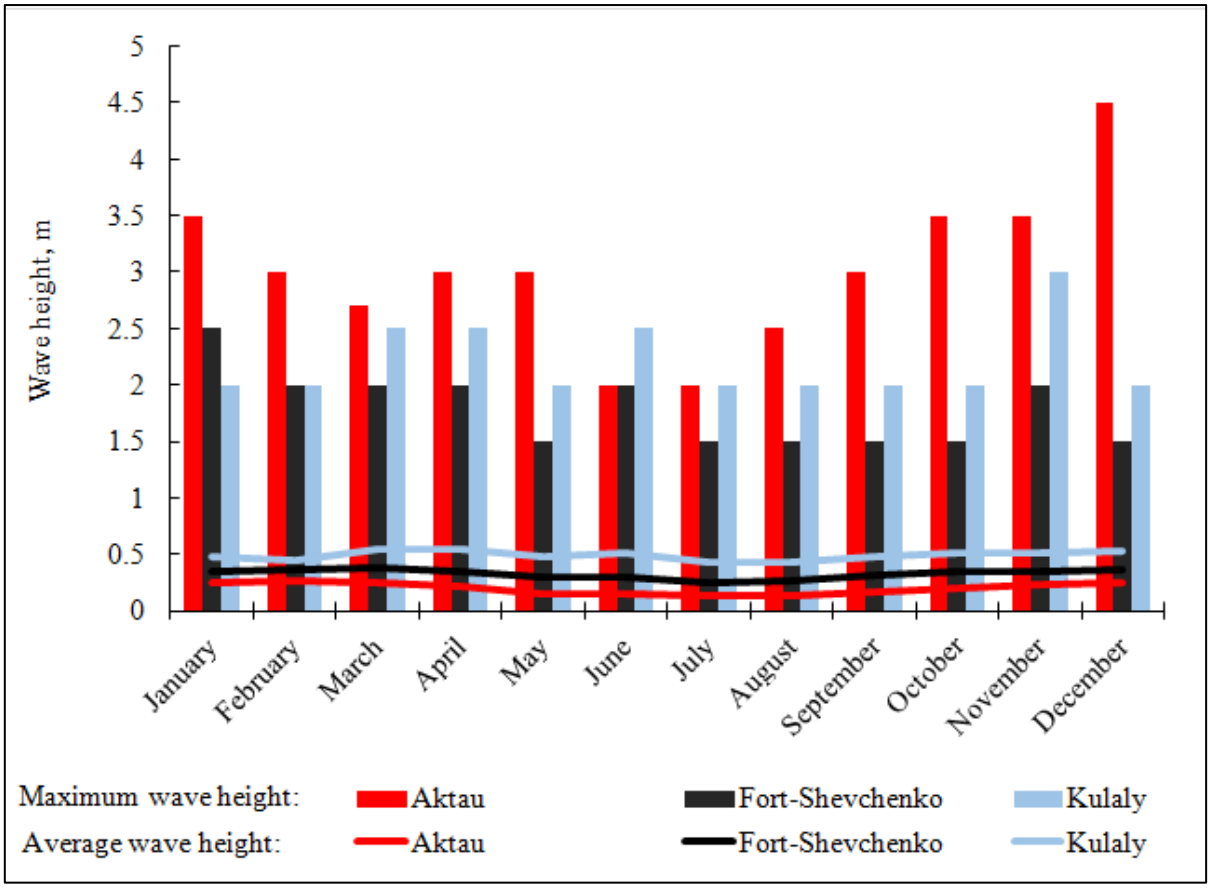


Figure 4. Monthly average and maximum wave heights in Aktau from 1980 to 2017, Fort-Shevchenko from 1993 to 2017, and Kulaly Island from 2001 to 2017.

3.3. Zoning maps for maximum waves

The wind wave zoning maps of the Kazakhstan part of the Caspian Sea show regions of wave height that depend on the wind speed and direction (Figure 5). Observation of waves on marine stations is conducted visually. The degree of excitement is characterized by the height of the observed waves. The height of the wave is determined by eye, according to the assessment of the five most noticeable large waves that passed in front of the observer's eye within 5 minutes. To convert the wave height to the degree of the wave, the scale of the number of waves is used (Table III) (Korovin & Timets 2000).

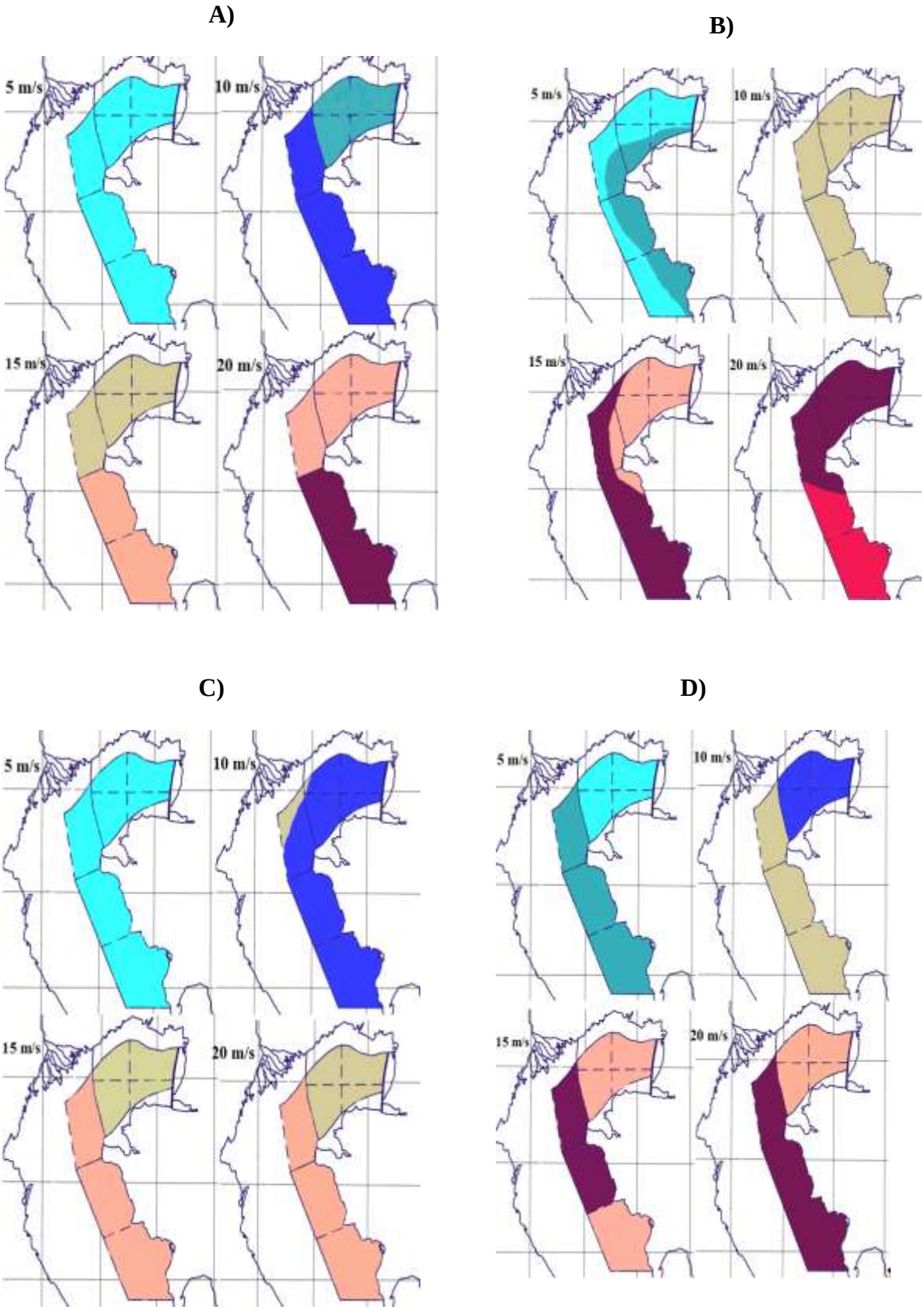
Table III. Scale of wave.

Wave height, m	Wind classification	Points	Zoning color
0	Not relevant	0	
up to 0.25	Weak	I	
0.25 – 0.75	Moderate	II	
0.75 – 1.25	A significant	III	

1.25 – 2.00	A significant	IV	
2.00 – 3.50	Strong	V	
3.50 – 6.00	Strong	VI	
6.00 – 8.50	Very strong	VII	
8.50 –11.0	Very strong	VIII	
>11	Exceptional	IX	

The zoning map was based on the “Atlas zoning of seas and oceans for hydrometeorological support of maritime activity” made by Roshydromet in 2009. Maps were built under the condition that the wind would be stationary, that is, within three days the wind of one speed and one direction would blow. Zoning maps were built with wind parameters of 5, 10, 15, 20 m/s and in 8 directions (C, NE, W, SE, S, SW, W, NW) using the SWAN model.

Analysis of the maps showed that with a weak wind the wave height can reach 1.25 meters with the wind direction to the northeast, southeast, southwest and northwest and the smallest in the west direction. With a strong wind with a speed of 10 m/s, the maximum wave height can reach 3.5 m in the Middle Caspian, for the northern part the wave can be up to 1.25 m in height, depending on the depth of the sea. At a wind speed of 15 m/s, the wave height in the waters of the Kazakh part of Caspian Sea is between 2 m in the North and 7 m in the Middle Caspian. According to model predictions, maximum wave heights can be formed in the Middle Caspian at wind speeds of 20 m/s and direction to the north-west and south-west.


A)
5 m/s
10 m/s
15 m/s
20 m/s
B)
5 m/s
10 m/s
15 m/s
20 m/s
C)
5 m/s
10 m/s
15 m/s
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D)
5 m/s
10 m/s
15 m/s
20 m/s

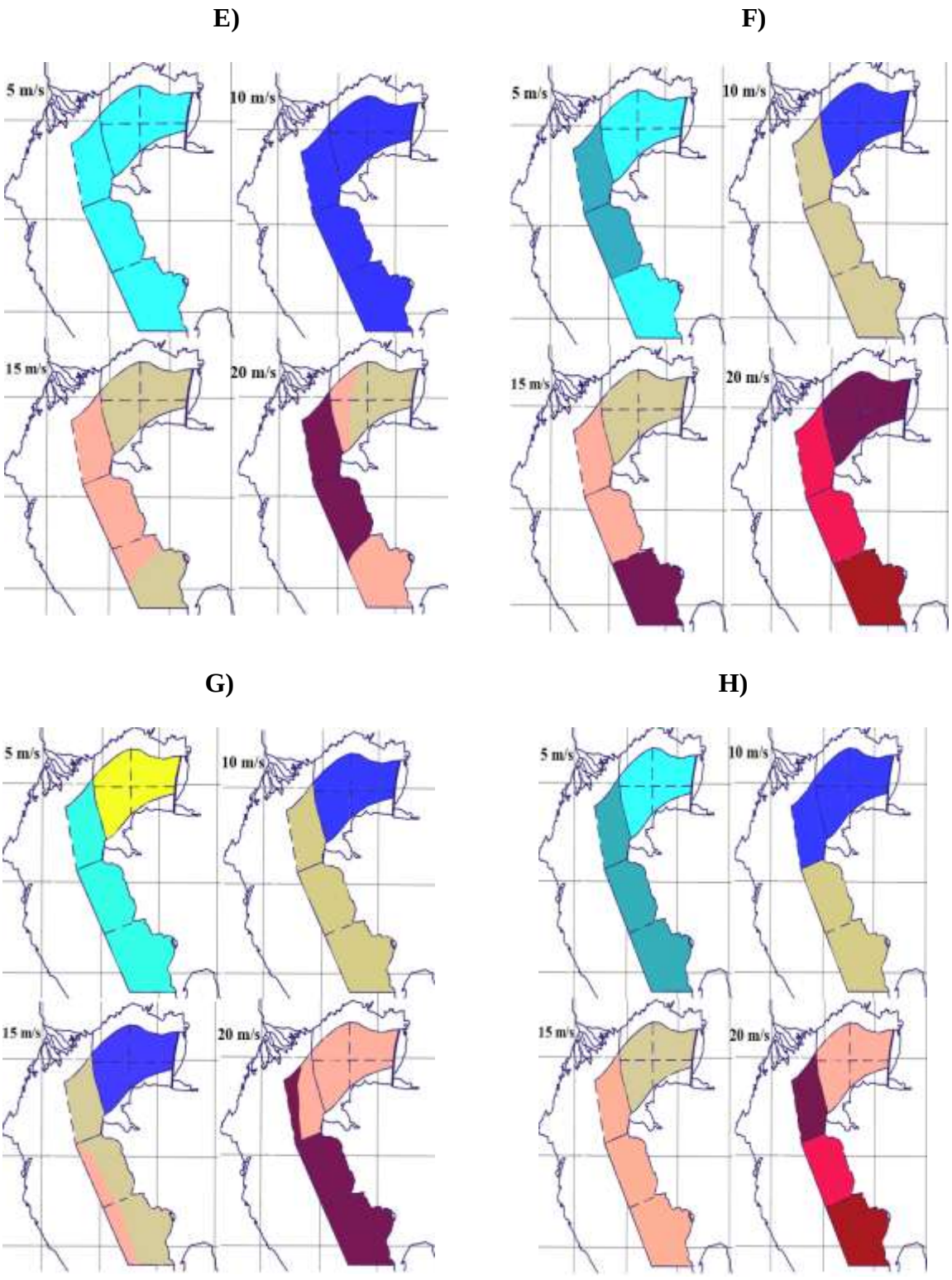

Figure 5. Zoning maps of the Kazakhstan part of the Caspian Sea by wave height in points for different wind directions: A) North, B) North-East, C) East, D) South-East, E) South, F) South-West, G) West, H) North-West.

4. Conclusion

Wave maps of the Caspian Sea are needed to serve sea transport and international cargo. Such maps can provide information and prevent accidents at sea. In order to produce wave maps, the wind and wave characteristics were analyzed for the Kazakh regions of the sea. The results show, that wave characteristics in the northern part of the Caspian Sea depend on the sea depth. In shallow waters, waves will be up to 1 m in height, and in the deep-water they reach 3 m or more. The highest wave heights for this region are formed at wind speeds greater than 15 m/s and directions northwest and southwest. The SWAN model predicted well the height and direction of waves for the deep middle part of the sea. But, for areas of the northeastern part of the Caspian Sea, where the sea is shallow, the results of modeling wave heights needed to be analyzed and edited, since in some places the predicted wave heights were very high, which is not typical for this region. The results provided the first wave maps in the Kazakh Caspian Sea that can be used to guide compilation of shipping routes.

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