Vol. 11. No.1. 2022

Contents available at:

http://www.crdeepjournal.org

DOI: https://doi-ds.org/doilink/10.2020-51948721/

International Journal of Environmental Sciences (ISSN: 2277-1948) (CIF: 3.654)
A Peer Reviewed Quarterly Journal

Review Paper

The Stormy Regime of Waves on the Black Sea Coast on the background of Global Warming: A Review

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ARTICLE INFORMATION

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Article history:
Received: 14-01-2022
Revised: 26-01-2022
Accepted: 10-02-2022
Published: 17-02-2022

Key words:
Wind, rough sea, storm, magnitude, wave

ABSTRACT

Significant indicators in the consideration of the changes in the hydrological regime of the Black Sea on the background of global warming are quantitative and qualitative indicators of storm loads that have changed a great deal over the last years. While considering the characteristics of hydrological mode we mainly used the observation materials of the Batumi Hydrometeorological Service (wave characteristics), because we have different regimes and directions of waves in each section of the Black Sea coast, which depends on many factors. We mainly focused on the processes of wave regimes of the last 15 years (2000-2015) and we will try to find out what the deviations are observed in comparison with the multi-year regime. In the period of observation (1961-1989), the west rhumb waves have a dominant direction - 72.64%, followed by the northwest direction - 16.77%, waves of north direction equal to 8,7% and the south-west waves are is 1,73 %. On the background of global warming, the quantitative characteristics of strong waves have changed. The number of days of 5 magnitude and more capacity storms have sharply increased (2003 to 2014) with 147 storms per day. Not only the number of 5-6 magnitudes of waves has increased, but since 2000, 3 cases of 7-magnitude storms have been reported for the first time. In the last fifteen years, the storm's internal distribution regime has changed with the impact of climate warming: the quantitative indicators of stormy days of 4, 5 and 6-magnitudes of waves from 1962 to 2003 were almost unchanged during the ten-year cycle period, and we did not have 7 magnitude waves at all. Quantitative features have increased almost 2 times and as mentioned above, there are also 7-magnitudes waves. According to multi-year regime, the period of their detection does not coincide as well.

Introduction

The Black Sea surface is characterized by frequent movement of cyclones, strong north and north-east winds, which is the best condition for the formation of wind waves. In the parallel to the seasonal change of wind speed, the average monthly point scale is also changing. In particular: In the Black Sea basin, almost everywhere, the gradual increase of the wind is observed from late August to late February, respectively, in August if an average point scale of waves is 2.8, in January and February, this index reaches 4 and is recorded in the central part of the basin (Leonov, 1960). The study of rough sea and storms is very important because they cause abrasive processes in the southwest coast of Georgia (Adjara). In the past century, the coastal area washed off by abrasive processes in the Adjara coastline exceeded several hundreds of hectares. During this period, in the district of Chorokhi confluence (along Daba Adlia), the coast retreated 200-400 meters and more in the depth of the land, and from Batumi to the river Natanebi, the coastal line retreated of shore with100 to 200 meters. Thus, the coastal region of Adjara is a high-risk zone of natural disasters. The risk is expressed during 3 - 4 magnitude storms. Such storms greatly damage homes and infrastructural facilities in the coastal areas, causing damage and destruction (Russo, 1984).

Materials and methods

Study area

The Black Sea is part of the World Ocean, so it is a matter of urgency what the impact of the processes in the World Ocean on the Black Sea hydrometeorological regime, in particular: on the level fluctuation, on the activity of storm processes and on the thermal regime of surface sea water.

Method

Accordingly, the main goal and objective of this paper is to develop and analyze the materials of the Black Sea hydrological regime obtained at various hydrometeorological stations and observatories, including: determination of fluctuation and intensity of storm activity. To better capture the picture, we divided the current processes into two parts: the first - until 2000, when climate change elements were clearly exposed to global warming, and the second - the last 15 years, where fluctuations in meteorological elements are clearly visible.

Result and Discussion

In the Black Sea, there are mainly wind waves, which are affected by continuous energy supply and impact In the coastal zone of Georgia. The geographic location of the Black Sea, its dimension, deep-water shorelines, weak coastline distribution, short-lived ice cover in the winter, frequent displacement of cyclones, strong north and northeast winds - all of which are the best conditions for the formation of wind waves. Along with the seasonal flow of wind speeds, the average monthly fluctuation changes as well. Namely: in the Black Sea basin, almost everywhere, there is a gradual increase of wind from August to the end of February. Accordingly, if we have an average temperature of 2.8 bali in August, it reaches 4 in January - February and is recorded in the central part of the basin. From March to August, the wind speed decreases slowly, so does the wind speed. For example, the highest average monthly fluctuation in the northwestern part of the Black Sea was observed in March and is 3.7 point, 2.8 in April, and 2.5 in July (Fig. 15), (Leonov,1960). In the same table, it can be seen that in the winter months 8 - 9 points are recorded in the western and northwestern regions of the Black Sea. Sea level rise due to climate change is one of the main indicators of vulnerability of the Black Sea coastal zone, which has also undergone significant changes in recent years. The processing and analysis of daily, regime-based observational materials on sea level fluctuations at the maritime hydrometeorological station of the Batumi Port from 1963 to 2014 showed that the perennial regime of sea-level fluctuations in Batumi has been disturbed and there are some interesting changes (Tab. 1. Fig. 1). Figure 16 shows the sea level average annual creeping fluctuation schedule in Batumi, where it is evident that there has been a trend of rising sea levels on the Adjara coast since 1985. The sea level has risen sharply over the last 30 years and the average annual level has exceeded 20 cm. Extreme (maximum, minimum) indicator of level fluctuations maintained an average annual amplitude of 50 cm(Shvangiradze, Metreveli,2008). Table 1. The average annual creeping fluctuation of the black sea level. (Batumi).

Table 1: Black Sea level average The annual creeping fluctuation process. (Batumi)

Year	Level (cm)	Year	Level (cm)
1963-1972	468	1975-1984	468
1964-1973	467	1976-1985	468
1965-1974	468	1977-1986	469,5
1966-1975	468	1978-1987	471
1967-1976	467,5	1979-1988	473,5
1968-1977	467	1980-1989	475
1969-1978	467	1981-1990	475
1971-1980	467	2002-2011	481
1972-1981	466,5	2003-2012	481,5
1973-1982	467	2004-2013	481,5
1974-1983	468	2005-2014	482

Source: Author (2015)

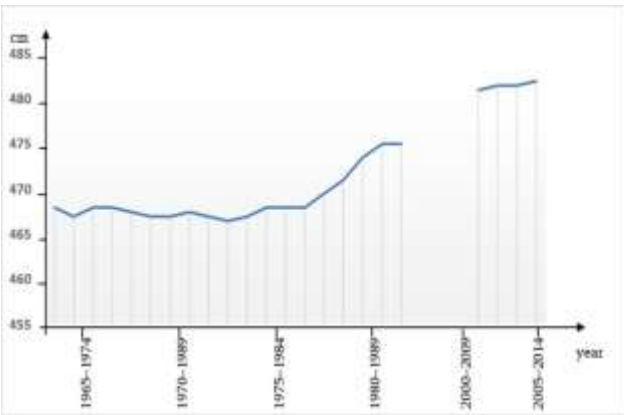

Fig 1: . Sea level average annual creeping fluctuation schedule. (Batumi)

It is interesting to see how the above mentioned process has affected other regions of the Black Sea. According to Poti Hydro-meteorological Station data, the Black Sea level fluctuation observation data show that by 2000 sea level has risen like Batumi sea and its seasonal fluctuations range from 495 to 515 cm. Graphs of the average annual creeping fluctuation of the sea level (Table 2, Fig. 2) show clearly the trend of sea level rise in Poti in recent years. The continuous increase in the curve confirms the abovementioned. Consequently, sea level has risen markedly over the past 14 years and the average perennial mark has exceeded 20 cm. Of course, there are also seasonal fluctuations in sea level rise and decline, but overall there is still a clear rise in the continuous regime. (Table 2. Average annual creeping fluctuation table of the Black Sea level. (Poti).

Table 2: Black Sea level average Annual creeping fluctuation table. (Poti)

Year	**2000-2009**	**2001-2010**	**2002-2011**	**2003-2012**	**2004-2013**	**2005-2014**
Level (cm)	500	502	502	503	503	504

Source: Authors (2015)

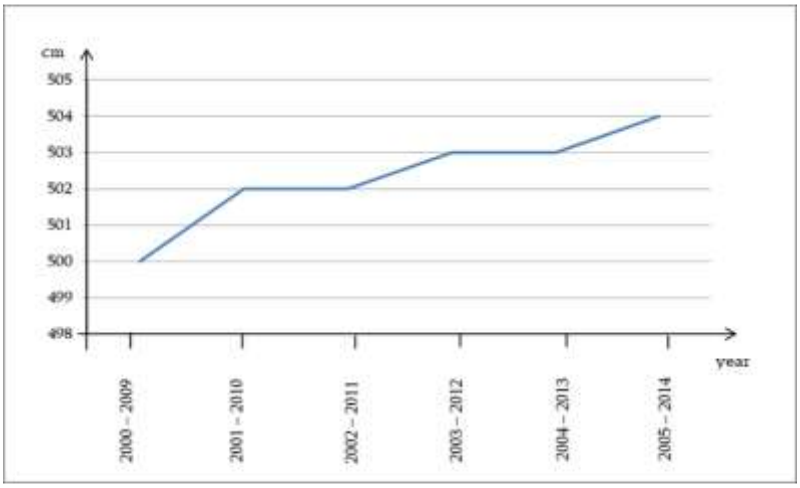

Fig 2. Sea level average annual creeping fluctuation schedule. (Poti) . *Source: Authors (2015)*

Against the backdrop of global warming, not only has the sea level hypsometric status changed, but also the mode of its annual fluctuation. According to the Batumi Hydrometeorological Station, autumn - winter minimum and spring - summer maximum (Fig. 3) were observed during the annual fluctuation of the level until 1989 (Fig. 3), whereas in 2004 - 2006 the annual flow was violated and characterized by an equal regime. In 2006–2013, a different form of level fluctuation (Fig. 3) was observed, characterized by winter-spring maximum and summer-autumn minimum, and during the 2014 annual peak the 500-cm peak again returned to the previous average. It is expressed as a perennial regime (470 cm) with equal course. (Fig. 3.)

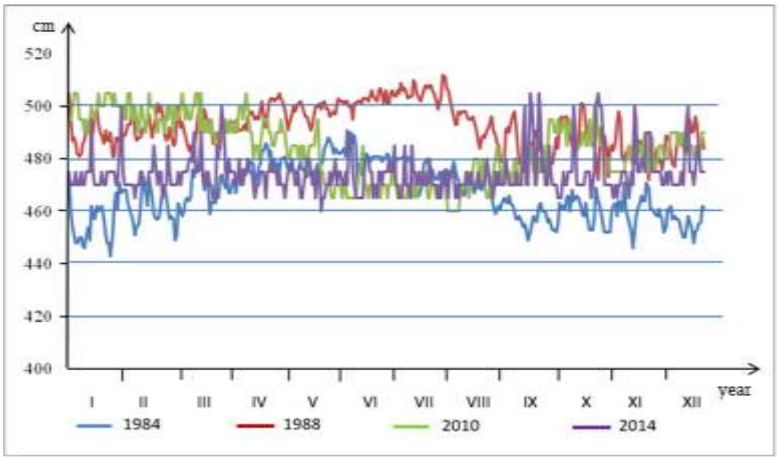

Fig 3. Annual Black Sea Fluctuation Regime. (Batumi). Source: Authors (2015)

A very interesting picture was given by the regime study materials of the two nearest hydrological stations, Batumi and Poti (up to 50 km), the processing and analysis of which showed that the average annual and average monthly movements of sea level fluctuation are almost identical. The above information is well illustrated on graphs of sea level fluctuation (Table.3 Fig. 4). For the last 15 years, as shown in the drawing, the Poti sea level has long been above 500 cm (the Poti sea level mark is always higher than Batumi because of its proximity to the confluence of the most rich-aqueous river Rioni in Georgia) and during that period its linear annual procession continues until 2010, then increases and continues to this day. The annual procession of Batumi is similar (Fig. 4), except that its benchmark is slightly lowered and the procession is almost the same. Average monthly sea level fluctuation (cm). (Batumi)

Table 3. Sea level fluctuation average monthly procession (cm). (Poti)

level						**Month (Poti)**						
Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2000	498	505	505	506	513	516	508	501	495	511	492	488
2001	492	498	505	512	510	511	506	497	498	491	493	497
2002	495	499	509	507	512	509	512	507	508	803	495	498
2003	504	501	497	496	493	484	493	198	494	500	495	497
2004	505	505	507	512	514	509	511	505	493	497	500	500
2005	503	509	506	509	495	507	511	507	510	503	501	505
2006	500	500	506	510	413	515	503	504	497	502	499	494
2007	494	497	501	501	497	502	500	493	493	488	485	500
2008	498	193	187	495	502	501	501	495	488	492	487	494
2009	493	498	502	502	505	501	504	487	499	499	498	502
2010	514	519	528	519	515	523	527	519	507	509	498	510
2011	519	520	514	510	509	514	510	509	502	500	504	492
2012	500	502	503	495	506	510	506	509	494	494	496	502
2013	504	505	515	516	515	515	522	515	510	505	498	507
2014	501	501	506	502	505	514	514	515	513	504	507	508

Source: Authors (2015)

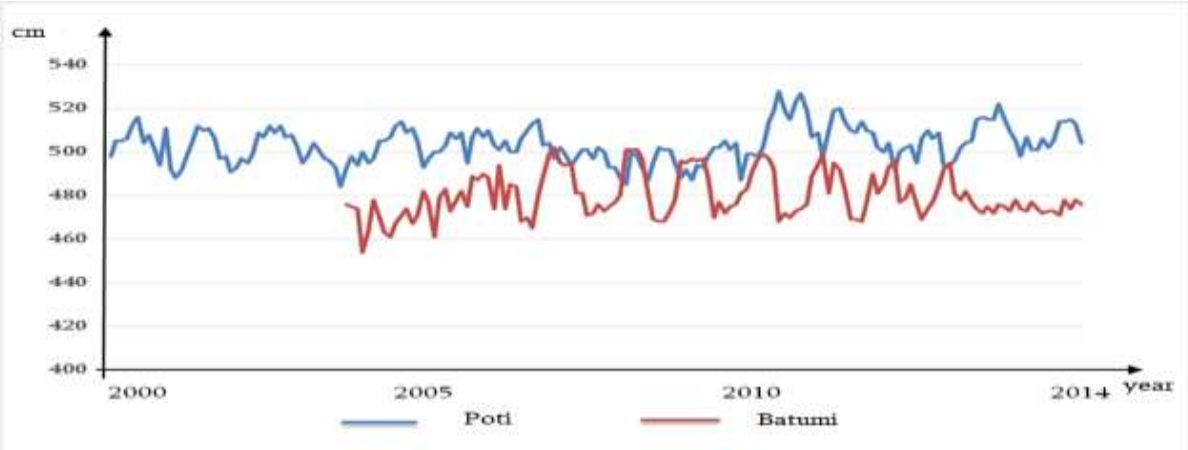

Fig. 4. Sea level fluctuation average annual procession. *Source: Authors (2015)*

Based on the data obtained from the fluctuations in the different regions of the Black Sea, when characterizing the average perennial regime, we note that the amplitudes in Batumi and Poti are between average absolute maximum and minimum, within the limits of 20-24 cm, and are almost equal and consequently, in Varna it equals 39-40 cm. which differs sharply from the eastern coast of the Black Sea and depends on the duration of the series of observations above. It should be noted that the amplitude of the average perennial level fluctuation in all regions is almost the same and varies within 20 cm (Table 29). Characteristics of the Black Sea Fluctuation Process after 2000.

Table 4: Characteristics of the Black Sea Fluctuation Process after 2000

	Station	**Aver. annual Max. (Cm)**	**Aver. annual Min.. (Cm)**	**Aver. annual Ampl.. (Cm)**	**Aver. month max. (cm)**	**Aver. month min. (cm)**	**Aver. month Ampl. (cm)**	**Abs. Max. (Cm)**	**Abs. Min. (Cm)**	**Abs. Ampl. (Cm)**
1	Batumi	492	471	21	505	451	54	512	437	75
2	Poti	515	494	21	528	484	44	551	464	84

Source: Authors (2015)

The average monthly sea level fluctuation in Batumi was 451 cm (November 1985), the average monthly peak in 1988 was - 505 cm (July 1988), the difference being an average monthly amplitude of 54 cm. The absolute minimum sea level in Batumi was 437 cm on November 25, 1985, and the absolute maximum was 512 cm on August 3, 1988, respectively, with an absolute amplitude of 75 cm. As for Poti, the average monthly minimum was 484 cm (June 2003) and the maximum was 528 cm (March 2010) with an average monthly amplitude of 44 cm. The absolute minimum was recorded on October 2, 2007 - 464 cm, and the absolute maximum was recorded on February 5, 2010 and amounted to 551 cm, therefore the absolute amplitude of the fluctuation is equal to 84 cm. In the context of global warming, researchers say, in the last 15 to 20 years, the global ocean level has risen by an average of 20 cm, with an average speed of 1 cm per year. Our observations have confirmed this, and the increase in the Black Sea level has exceeded 30 cm on average in the last 25 - 30 years, hence the annual rate of increase is the same - average 1 cm per year.

The second indicator when considering changes in the characteristics of the Black Sea hydrological regime in the context of global warming is the quantitative and qualitative indicators of storm surges, which have changed considerably in recent years compared to the perennial regime. In discussing the characteristics of the second indicator, we have mainly used the regime observation materials (wave characteristics) of the Batumi Hydrometeorological Service, as we have different regimes of waves and directions in each section of the Black Sea coast, which depend on many factors. As we discussed in detail in the Black Sea regime in Chapter III, this chapter will focus mainly on the wave regime movement of the last 15 years (2000 - 2015) and try to illustrate the deviation compared to the perennial regime on the Batumi example. Based on the above, we have built up statistical and energy indicators that have given us a pretty interesting picture (Table: 5, 6, Fig: 5,6).

Table 5: Statistical indicator of the wave disturbance of the Black Sea coast zone of Adjara (2000-2011)

Direction	**N**		**NW**		**W**		**SW**		**S**		**Bowl**	
magnitude	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
1	3	0.07	202	4.70	1185	27.60	321	7.47	1	0.02	1712	39.86
2	1	0.02	137	3.19	1031	24.00	474	11.04	1	0.02	1644	38.27
3	2	0.05	44	1.02	295	6.87	288	6.70			629	14.64
4			24	0.56	87	2.02	136	3.17			247	5.75
5			9		15	0.35	30	0.70			54	1.26
6					8	0.18	1	0.02			9	0.20
7												
8												
Bowl	6	0.14	416	9.68	2621	61.02	1250	29.1	2	0.04	4295	99.98

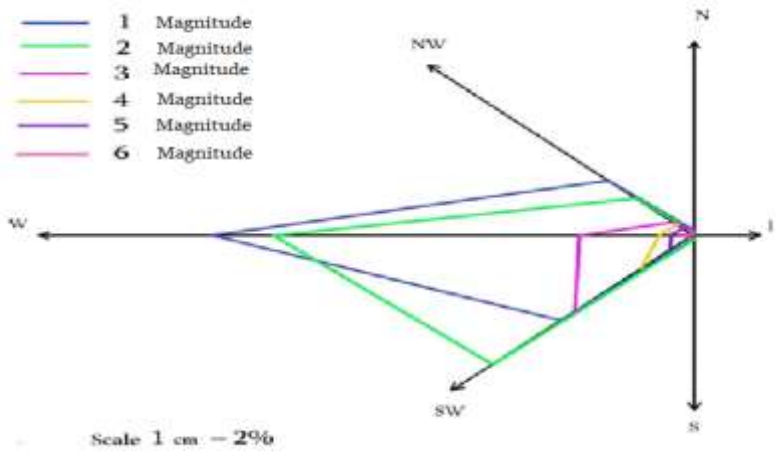

Fig.5. Statistical indicator of the wave disturbance of Adjara Sea coast zone (2000 - 2011). Source: Authors (2015).

Table 6; The energy indicator of the wave disturbance of the Black Sea coast zone of Adjara (2000-2011)

Direction		**N**		**NW**		**W**		**SW**		**S**		**Bowl**	
magnitudee	**K**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
1	0,2	0.6	0.01	40.4	0.62	237	3.65	64.2	0.99	0.2	0.003	342.4	5.27
2	1.0	1.0	0.01	137	2.11	1031	15.87	474	7.30	1.0	0.01	1644	25.3
3	2,3	4.6	0.07	101.2	1.56	678.5	10.44	662.4	10.20			1446.7	22.27
4	6,3			151.2	2.33	548.1	8.44	856.8	13.19			1556.1	23.96
5	19,6			176.4	2.71	294	4.52	588	9.05			1058.4	16.28
6	49,8					398.4	6.13	49.8	0.77			448.2	6.90
7													
8													
Total		6.2	0.09	606.2	9.33	3187	49.05	2695.2	41.5	1.2	0.013	6495.8	99.98

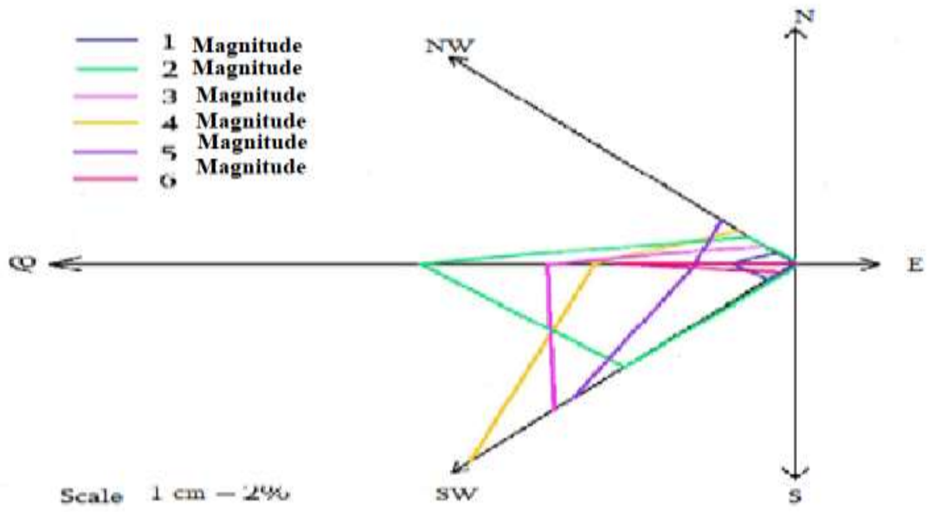

Fig.6: Energy indicator of the wave disturbance of Adjara Sea coast zone (2000-2011). *Source: Authors (2015)*

In the statistical indicator tables, the number of different wave cases during the observation period is denoted by n, and the multiplication of the corresponding coefficients of n in the energy indicator shows the wave power. Based on the graphical representations of the statistical and energy indicators discussed in Chapter III (Table. 7, 8, Figs. 7,8.) we can note that the quantitative repetition rate of waving is shown in table 30. Statistical Indicator of the Black Sea Coast Zone of Adjara (2000 - 2011).

Table 7: Statistical indicator of the wave disturbance of the Black Sea coast zone of Adjara (1961-1989). *Source: Author (2015)*

Direction	**N**		**N-W**		**W**		**S W**		**S**		**Bowl**	
magnitude	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
1	327	3,27	46	4,06	980	9,8	28	0,28	8	0,08	1749	17.49
2	450	4,5	935	9,35	3398	33.98	96	0,96	6	0,06	4885	48.85
3	72	0,72	231	2,31	1505	15.05	36	0,36	1	0,01	1845	18.45
4	19	0,19	99	0,99	1149	11.49	10	0,1	1	0,01	1278	12.78
5	2	0,02	6	0,06	222	2,22	3	0,03	1	0,01	234	2,34
6					10	0,1					10	10
7												
8												
Bowl	870	8,7	1677	16.77	7264	72.64	173	1.73	17	0.17	100.01	100.01

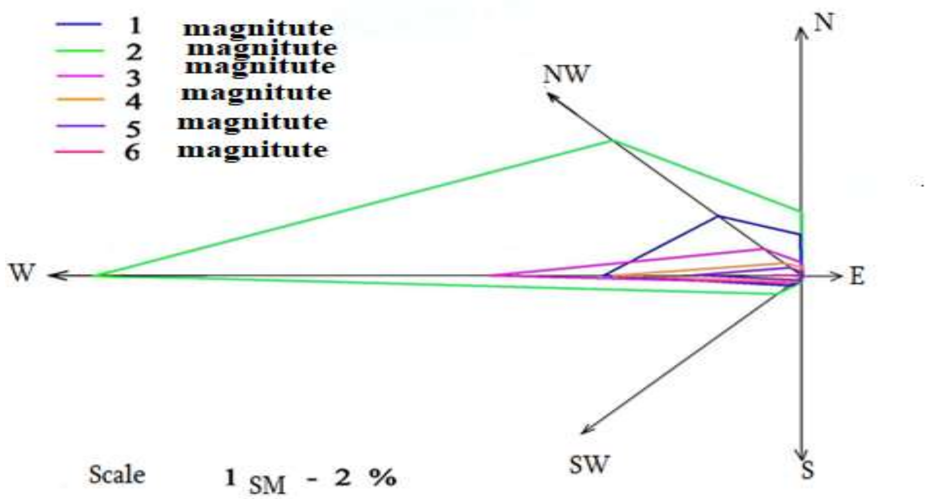

Fig 7: Statistical indicator of the wave disturbance of Adjara Sea coast zone (1961-1989). *Source: Authors (2015)*

Table 8: The energy indicator of the wave disturbance of the Black Sea coast zone of Adjara (1961-1989). *Source: Authors (2015)*

Direction magnitude	K	W		NW		W		S W		S		Bowl	
		n	%	n	%	n	%	n	%	n	%	n	%
1	0,2	65,4	0.29	81,2	0.36	19,6	0.09	5,6	0,02	1,6	0,01	173.4	0,77
2	1.0	450	2	935	4.17	3398	15.14	96	0,43	6	0,02	48.85	21.76
3	2,3	165.6	0.74	531.3	2.37	3461.5	15.43	82,8	0,37	2,3	0,01	4243.5	18.92
4	6,3	119.7	0.53	623.7	2.78	7238.7	32.26	63	0,28	6,3	0,03	8051.4	35.88
5	19,6	39,2	0.17	117.6	0.52	4351.2	19.39	58,8	0,26	19,6	0,08	4586.4	20.42
6	49,8					498	2.22					493	2,22
7													
8													
Bowl		839.9	3.73	2288.8	10.2	18967	84.52	306.2	1,36	35,8	0,15	22437.7	99.97

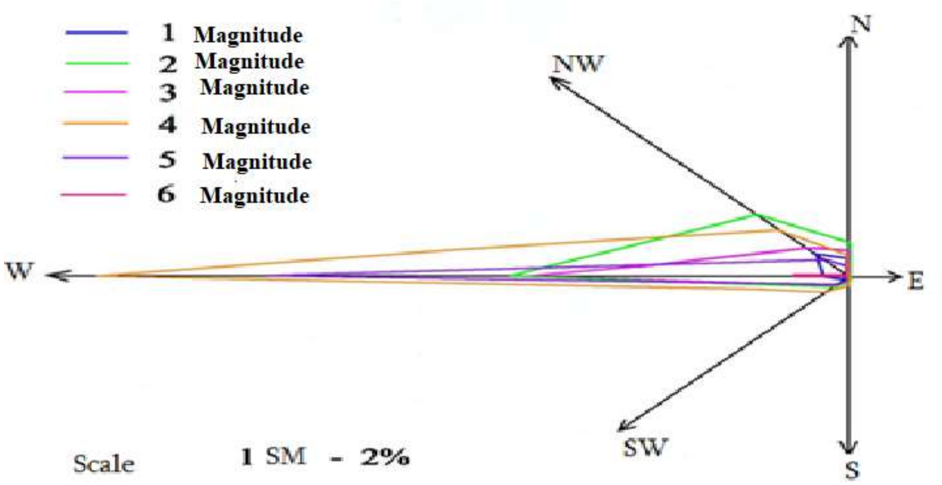

Fig 8: The energy indicator of the wave disturbance of the Adjara Sea coast zone (1961-1989). *Source: Author (2015)*

During the observation period (1961 - 1989), the west rhumb waves have prevailing direction 72.64% for the Adjara coast, followed by the northwest direction - 16.77%, the north direction waves - 8.7% and, at last, the southwestern - 1.73%. %. The statistical indicator of the 2000 - 2011 years (Table. 5, Fig. 5) gave a different picture when compared to the perennial regime. Accordingly: the prevailing west direction remained at 61.02%, while the north / west direction declined sharply to 9.68% and moved from third to second place according to the repeatability. West directional waves almost disappeared and made up 0.14% and increased south / west directional waves - 29.1%, which shifted to II from the IV place according to the repeatability. Not only the quantitative characteristic of repetition has changed, but also the direction of action of the wave and the north – west waves were replaced by the south / west waves, which were expressed both in terms of the number of statistical indicator and the energy indicator (Fig: 5, 6). It is also noteworthy that despite the increasing frequency of the westward currents, the south / west direction surges surpassed with their capacity (Fig. 6).

Conclusion.

Quantitative characteristics of strong waves have also changed (Table 9). The number of days of storms of 5 magnitude and over is also as follows: according to the 10-year interval, if there were 82 days between 1962-1971, there were 97 stormy days in 1978-1988 and in 2003-2014 there were – 147 stormy days. It is also noteworthy that not only has the number of 5-6 magnitudes increased, but 3 cases of 7 magnitude storms have been reported for the first time since 2000. In the last fifteen years, climate change has also changed the intra-annual distribution of storms: if the 1961 to 2003 the quantitative indicator of stormy days of 4, 5, and 6 magnitudes were slightly changed over a nearly ten-year cyclical period, and we had no 7 magnitudes at all, the quantities almost doubled and as mentioned above 7-magnitude waves also appeared. Period of detection does not coincide as well:

Stormy waves are mostly observed in late autumn (November - December) and in winter (early February - March). In the last period, from 2003 to 2014 stormy waves were quite different. In the last decade, some strong winds have also been observed in summer. It is also worth noting that the 2015 - 2016 winter storm season went without any strong waves (only two 5-magnitude waves were observed in November 2015 and in the winter – spring of 2016 passed without any strong waves), which was the first time in the observation process. It is possible that this storming process will be repeated in summer due to regime change. The overall nature of the repetition of only 4 magnitudes and fewer storm modes remained unchanged.

Table 9: The characteristics of the Black Sea storm intensity (5 magnitudes and more)

Year	**Capacity and quantity of storms**			
	4 magnitute	**5 magnitute**	**6 magnitute**	**7 magnitute**
1962-1971	326	76	6	–
1978-1988	643	95	2	–
2003-2014	272	128	16	3

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