Assessment of the feasibility of a conservative forecast of changes in the black sea level, taking into account the prehistory of the hydrothermal regime of its catchment area

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Abstract. Changes in the water surface level at any part of the World Ocean coast significantly affect the intensity of coastal destruction, and can cause considerable damage to the population and ecosystems of coastal zones. When planning measures to protect the Black Sea coast from the dangerous consequences of further sea level rise, its forecast is necessary, which has satisfactory justification and sufficient advance time. Existing predictive models ensure the development of forecasts with the required advance time, but often their justifiability is low. Therefore, the assessment of the feasibility of forecasts of sea level changes corresponding to various scenarios of further changes in the regional climate is an urgent problem of climatology, environmental safety and environmental management. The scenario of further changes in the indicator under consideration, which assumes that their statistical properties will remain the same in the future as they were in the past, is among the likely ones. To develop a forecast of the process under study that corresponds to this scenario and is optimal by the criterion of minimum standard error, the method of linear multiple regression can be applied. The main factors determining changes in the Black Sea level are water balance characteristics, in particular river runoff, whose contribution to the total volume of water entering the sea is significant and depends on the area of the catchment area and the amount of precipitation. The purpose of this work is to develop forecasts of sea level changes based on taking into account changes in the hydrothermal regime of the catchment area, and to assess their feasibility with a 1-year lead time. When assessing the feasibility of forecasts, the prehistory of changes in the Black Sea level according to measurements from the Yalta and Sevastopol marine hydrometeorological stations and the hydrothermal regime of its catchment area are taken into account. The composition of predictors of predictive models has been determined, which ensures satisfactory justification of their forecasts. It has been established that the suspension of

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the Black Sea level rise in 2011-2023 was largely caused by changes in the hydrothermal regime of its basin.

1 Introduction

A significant environmental factor that largely determines the safety of the population and the state of ecosystems of various parts of the Black Sea coast, as well as leading to the destruction and reshaping of the shores, are changes in its level. When planning measures to protect each site from the dangerous consequences of these changes, a forecast is needed that would have satisfactory justification and sufficient advance time. One of the most likely scenarios for changes in the level of the Black Sea is a conservative one, in which its statistical properties will not change in the future.

The solution to this problem is of the greatest interest for areas of the Black Sea coast that are densely populated, economically developed and have significant recreational potential. One of them is the section of the southern coast of the Crimean Peninsula between the points of Sevastopol and Yalta. The presence of more than a century of observations of sea level at these points, the absence of vertical movements of the earth's crust makes it possible to use the level measurement data at these points to assess variability on various time scales.

The main reason for changes in the water level of the Black Sea is the variability of its water volume, formed mainly by water-balance components, such as components of water exchange through the straits (Bosphorus and Kerch), as well as the freshwater budget, i.e. the difference between the arrival of fresh water (precipitation and river runoff) and their consumption due to evaporation. Quite a lot of works have been devoted to the study of the water balance of the Black Sea, for a long time the issues of studying the water balance characteristics of the Black Sea were studied in the Sevastopol branch of the N.N. Zubov State Oceanographic Institute, the main results were published in [6, 10, 12-17, 22].

In this paper, statistical relationships of long-term sea level values with changes in the hydrothermal regime of its catchment area are investigated and sea level changes are predicted on their basis. The formation of river flow volumes in the catchment area largely determines the dynamics of changes in the volume of marine waters, and, consequently, the level of the Black Sea. The volume of fresh river waters entering the Black Sea depends on the catchment area of the river basin and the amount of precipitation, as well as on the intensity of evaporation from the catchment area. In turn, the amount of precipitation and the intensity of evaporation are associated with thermal and wind conditions in the catchment area.

Due to regional climatic changes occurring against the background of global warming and aridization of the Black Sea territories in recent decades, one can expect an increased influence of the hydrothermal regime of the catchment area on the formation of the Black Sea level. The hydrothermal regime of the Black Sea catchment area should be understood as long-term changes in surface air temperature and the amount of precipitation in the catchment area of rivers flowing into the sea.

According to [12], 211 rivers flow directly into the Black Sea or through estuaries. The river flow into the Black Sea, according to physical and geographical zoning, consists of the flow of rivers in the northwestern part, Crimea, the Caucasus, the Turkish, Bulgarian and Romanian coasts [6]. According to various estimates, the average annual flow of rivers into the Black Sea varies quite widely from 287 to 480 km3/year [11]. According to [22], the total catchment area of the Black Sea basin is 1,857 thousand km2, the annual total river flow is 355.6 km3/year. About 74% (263.2 km3/year) of the total flow into the Black Sea falls on its northwestern part (the Danube, Dnieper, Dniester rivers), and 58.5% of the total flow is on the Danube River. The flow of the rivers of the Black Sea coast of the Caucasus and from the territory of Turkey, according to [9, 24], is 52.5 and 45.6 km3/year, respectively (respectively 14.8 and 10.6% of the total flow of rivers into the Black Sea). The flow of the rivers of Bulgaria, Romania (without the Danube River) and Crimea is not significant (~2.2 km3/year) [22].

To develop a forecast of sea level change that corresponds to a conservative scenario and is optimal by the criterion of minimum standard error, the method of linear multiple regression can be applied [4, 8, 20].

According to it, the forecast Y k of the studied process y k can be described by a model:

$$Y_k = C_0 + C_1 X_{1,k-1} + C_2 X_{2,k-1} + C_3 X_{3,k-1} + \ldots + C_N X_{N,k-1} \quad (1)$$

where k (k=2001, 2002, ..., K+2001) is the year to which the forecast being developed corresponds;

X_{1k-1}, X_{2k-1}, X_{3k-1}... X_{Nk-1} are predictors of the studied process y_k, which are selected among its factors that are ahead of it at one time or another;

K is an integer constant equal to the length of the time series of the process under study and its factors;

N is an integer constant not exceeding K (number of predictors);

C_0, C_1,... C_N are the coefficients of the multiple regression equation (real constants), selected to provide a minimum I

$I=E_k\{(Y_k- y_k)^2\}$,

E_k is the operator of mathematical expectation, which is calculated over the entire range of values k.

Changes in the level of the Black Sea in the future may occur not only according to a conservative scenario. Therefore, their forecast, developed using this method, may not be optimal. Nevertheless, such a forecast may be characterized by satisfactory justifiability, which is largely determined by the composition of the predictors of the model (1) [8]. The probability of the presence of this property in the forecast of the studied process in the future is increased if the same property was manifested in the background available to study.

It was found that the justifiability of the forecast under consideration may be acceptable with a high probability if its development mainly took into account factors whose statistical links with the studied process were strengthened in the past, and their total contribution to its average power exceeded 50% [20].

One of the main factors of changes in the Black Sea level is the variability of the components of the sea's water balance on seasonal and interannual scales and variations, which are mainly determined by changes in the hydrothermal regime of its catchment area [1 – 3, 7, 13, 18, 19].

Numerous hydrometeorological stations of Roshydromet, as well as similar departments of Eastern European countries, Georgia and Turkey, have been monitoring changes in air temperature and precipitation amounts in the Black Sea catchment area for many decades. The results of this monitoring, as well as the same information obtained at other hydrometeorological stations of the world, are the basis for a number of global atmospheric reanalysis, which describe changes in air temperatures and precipitation amounts for any parts of the earth's surface.

One such reanalysis is ERA-5 [23], supported by COPERNICUS. This reanalysis describes the changes in hourly average air temperatures in various layers of the atmosphere over any parts of the Earth's surface, as well as the hourly amounts of precipitation falling on them, which correspond to the nodes of the coordinate grid in increments of 0.25 o x0.25 o and occurred in the period from 01.01.1959 to the present. At the same time, multiple regression forecasts of the studied process, taking into account such factors, have not been previously developed for the Black Sea basin, and their justifiability has not been evaluated.

To make decisions on the protection of certain sections of the coast from the dangerous effects of sea level change, forecasts of this process with a 1-year lead time are most important. For this reason, the assessment of the feasibility of such forecasts is of considerable theoretical and practical interest.

The purpose of this work is to assess the feasibility of conservative forecasts for the coming year of changes in the average annual levels of the Black Sea for these representative points of its coast, in the development of which, as predictors of the prognostic model, the prehistory of indicators of the hydrothermal regime of the Black Sea catchment basin is taken into account.

To achieve this goal, the following tasks have been solved:

Determination of the composition of predictors of the model (1) of the predicted process, whose connections with it were significantly strengthened in the XXI century.

Assessment of the feasibility of forecasts of the studied process, developed taking into account the identified factors.

2 Study methodology

As factual material on changes in the average annual levels (hereinafter referred to as AAL) of the Black Sea, information from the data bank of the the Sevastopol branch of the N.N. Zubov State Oceanographic Institute was used, which is based on the results of observations made at the hydrometeorological stations Sevastopol and Yalta in the period 1874-2022. The dependences on the time of the AAL of the Black Sea according to the measurements of hydrometeorological stations Sevastopol and Yalta are shown in Fig.1.

As follows from Figure 1, in the period 1874-1912, the values of the AAL for the representative points under consideration differed significantly, the reason for which may have been the imperfection of the measurement methodology used.

In the period 2013-2000, the AAL in Yalta and Sevastopol increased significantly with average speeds of 2.2 mm/year and 1.46 mm/year, respectively, which confirms the validity of the estimates obtained in [1, 3, 13]. In the period after 2011, no significant trends in changes in the AAL for the same points were revealed, which may be a consequence of the warming (aridization) of the climate in its basin and a decrease in the freshwater balance of the sea (river runoff plus precipitation minus evaporation).

It is easy to see that periods of up to 10 years in which the AAL of the Black Sea also significantly decreased were observed earlier. In particular, this happened in the period from 1940 to 1949, in which climate warming did not occur. Therefore, the conditionality of the current trend of changes in the level of the Black Sea by climate warming in its basin is not obvious and needs to be confirmed.

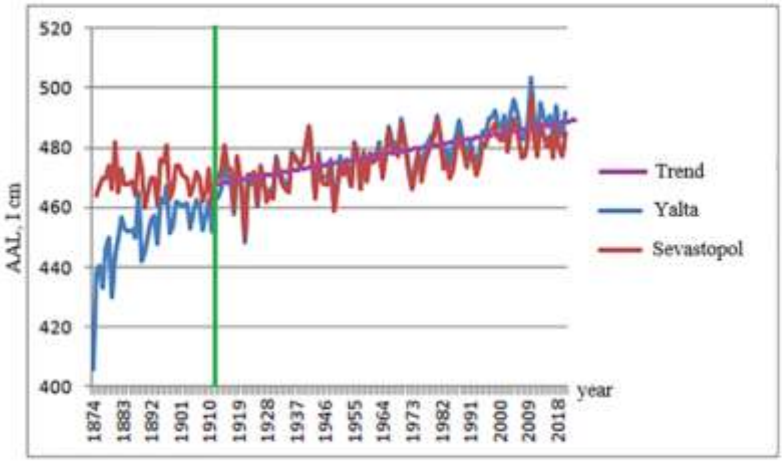

Fig.1. Dependences on the time of the Black Sea AAL according to the measurements of hydrometeorological stations Sevastopol and Yalta.

The relevant information from the ERA-5 reanalysis was used as factual material reflecting changes in hourly average air temperatures and precipitation amounts (for each hour) in the Black Sea catchment area from 1979 to 2023 [26]. Testing of information from the reanalysis was carried out by comparing estimates of average monthly air temperatures (hereinafter AMAT) and monthly total precipitation (hereinafter MTP) calculated using it for 46 points in the Black Sea catchment area with estimates of the same indicators based on the results of actual observations, which are presented in [25]. Testing has confirmed the acceptability of using this information to solve the tasks set.

The method of solving the first task assumed the search for factors of interannual changes in the AAL of the Black Sea, the connections of which with them increase over time. The search for such factors was carried out among the elements of their initial set, which included interannual changes in the average for the territory of the Black Sea basin AMAT and MTP for any months. It was assumed that the time series that describe the factors under consideration may be no more than 5 years ahead of the predicted process (for the development of a forecast with a planning and forecasting for 2024, the values of AMAT and MTP for any months of the period 2019 – 2023 can be used).

The AMAT and MTP time series, containing 44 members each, are formed from information on hourly average air temperatures and hourly total precipitation in the points of the Black Sea catchment basin, which are presented in the ERA-5 reanalysis, and averaged over its entire territory.

As an example, Figure 2 shows the time dependences of the AMAT and MTP for the Black Sea catchment area corresponding to January and June.

It follows from Figure 2 that in the interannual changes of the MTP for 1979 – 2020, corresponding to the catchment area of the Black Sea for January, there is a significant decreasing trend (its angular coefficient is minus 0.19 mm/year). The trends corresponding to the variations of the MTP for June, as well as the AMAT for June and January, are significant and increasing (their angular coefficients are 0.3 mm/year, 0.038 o/year and 0.062 o/year, respectively).

It is clear from Figures 1 and 2 that the processes under study and their factors represent complex fluctuations. The amplitudes of these fluctuations are so large that the corresponding trends, estimated over shorter periods of time, may turn out to be insignificant.

As a characteristic of the relationship of each of the factors under consideration with the process under study, the value of their pair correlation coefficient was considered, which was calculated in a "sliding window" of 20 years in length. Given the length of the rows studied, a total of 17 such "windows" were considered. When determining the value of this coefficient corresponding to a certain window, the trends present in the compared time series were compensated.

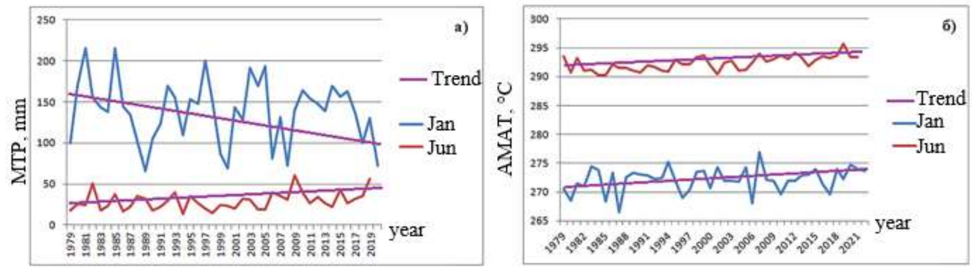

Fig. 2. Time-dependent indicators of the Black Sea catchment area for some months: a) AMAT (° K) and b) MTP (mm).

The factors for which the linear trend of changes in the values of this coefficient was increasing and significant were identified. A similar statistical conclusion was made if the probability of its validity was at least 0.95. It was assumed that the deviations of the calculated values of the correlation coefficient of the considered time series from their linear trend obey the normal distribution law (its validity was confirmed using the Fisher criterion). Taking this into account, the feasibility of the condition was checked to assess the desired probability:

$$17|ACLT|>1.65\ RMSD \quad (2)$$

where ACLT is the angular coefficient of the linear trend of the time series, reflecting the dependence of the correlation coefficient of the compared processes on the year of the beginning of the "sliding window" of 20 years in length, for which it is calculated;

RMSD is the root mean square deviation of the values of this coefficient from the mentioned linear trend.

| | is the operator for calculating the absolute value of the number to which it is applied.

When solving the second task, as an indicator of the feasibility of the forecast, we considered the frequency with which the change in the predicted value of the AAL for the considered points on the Black Sea coast occurred in the same direction with respect to the value of the AAL for the previous year as the actual change in this indicator. Taking into account the total number of "windows" under consideration, a total of 17 such forecasts have been formed.

During the development of each forecast, the verification of the model (2) was carried out for the considered "window", the predictors of which are the factors identified in solving problem 1. At the same time, the Multiply Regression program was used in All effects mode, from the Statistika package. Using the same program for this "window", the total contribution Θ of the identified predictors of the model (2) to the average power of the studied process was determined. A time series is formed from the values Θ, for which, as a characteristic of the trend, the value of its ACLT is estimated. The reliability of the conclusion about the significance of the revealed trend of changes Θ was checked by criterion (3).

When determining the AAL forecast for the coming year for the considered "window", the calculated values of its coefficients, as well as the values of X nk-1 corresponding to the desired year (related to the next "window") were substituted into ratio (2). The value of Y 20 calculated in this way was the desired forecast.

So, for example, when determining the conservative forecast of the AAL for a certain point for 2020, the verification of model (2) was carried out using a segment of a series of the AAL for the same point for 2006-2019. At the same time, the time series of the studied factors for the period 2004-2018 were used as predictors.

The forecast of the AAL for 2020 is calculated using calculated coefficients, as well as predictor values of the same model for 2005-2019.

As follows from the above, the research methodology is based on the assumption of the normality of the law of distribution of forecast errors, the validity of which is confirmed using the Fisher criterion. At the same time, it is known that the specified criterion is ineffective when checking the validity of the hypothesis of the normality of the distribution law for samples of small length. Therefore, the reliability of the conclusion about the normality of the studied law, obtained from a sample with a length of only 17, is low.

Nevertheless, estimates of the feasibility of the forecast under consideration for the coming year were obtained without using any simplifying assumptions and are quite correct. Therefore, it is advisable to take into account the AAL forecasts developed according to the above methodology for the considered points of the Black Sea coast for the coming year when planning economic activities.

3 Study results

When solving the first problem, for each of the 17 "sliding windows" formed from the AAL time series for the points of Yalta and Sevastopol, the value of its correlation coefficient (k) with the segments of the AMAT and MTP time series for all months that are 1-5 years ahead of the studied series was calculated. From the results obtained, 60 time series were compiled for each point, reflecting the dependence of k on the year of the beginning of the considered "sliding window". For each such time series, the value of ACLT and RMSD was estimated, which made it possible to identify time series k, the trends of which are significant.

It is obvious that an increase in the statistical relationship between a number of AAL and a number of any factor under consideration occurs if the value of k corresponding to the first window is modulo inferior to the value of the same coefficient for the last window, and the calculated value of the ACLT of the corresponding series k is significant. Guided by these considerations, for each representative item, those of the factors under consideration have been identified, the links of which with the corresponding number of the AAL have significantly increased over the studied period of time.

It is established that the desired factors, both for hydrometeorological stations Yalta and Sevastopol, are interannual changes:

- AMAT for June, 1 year ahead of the AAL time series (hereinafter AMAT June, -1); January, -3 and -4; July, -5; August, -5;
-MTP June, -1; December, -1 and -5; August, -2.

The analysis of time series k corresponding to the listed factors showed that for each of them the values of k at its beginning are not significant, as a result of which the forecasts developed for the first windows of the AAL series are highly likely to fail. To prevent this, another factor was added to these factors, AMAT May, -2, for which the values of k were significant at the beginning of the corresponding series of k, and gradually decreased in the future.

Examples of the dependence of k on the year of the beginning of the "sliding window" of the AAL for hydrometeorological station Yalta, corresponding to the factors used as predictors of the model (1), are shown in Fig. 3. As follows from Figure 3, the strength of the statistical relationships of the AAL for Yalta, estimated in a "sliding window" of 20 years long, with all the factors for which time dependences k are represented on it, increases as the number of this window increases (except for AMAT May, -2, for which it decreases). A similar type has the same dependencies for hydrometeorological station Sevastopol.

The nature of the dependencies under consideration indicates that a significant decrease in the strength of the identified relationships is unlikely in the coming years. Therefore, if the forecasts developed with them in mind had satisfactory justifiability in the past, then acceptable justifiability is quite likely in the near future. In this regard, the search for factors that are advisable to use in the development of the forecasts under consideration must be repeated annually using newly obtained data.

In solving task 2, the verification of models of interannual changes of the AAL corresponding to all the considered "windows" was carried out. At the same time, for each "window", the relative contribution Θ of the identified predictors of the model (1) to the average power of the studied process is estimated. The dependences of this indicator for hydrometeorological stations Yalta and Sevastopol on the year corresponding to the end of the considered "sliding window" are shown in Fig.4. It follows from the figure that the changes over the period 2005-2021 in the relative contributions Θ of the identified results of modeling the interannual changes of the AAL for hydrometeorological stations Yalta and Sevastopol to their average capacity, from the year of completion of the "sliding window" for which they were calculated, were in the nature of fluctuations with a period of about 11-12 years. At the same time, in the period 2015-2021, the tendency to increase Θ prevails. In general, for the entire studied period, the values of the indicator in question varied from 0.440 to 0.871. Consequently, the influence of the identified factors on the degree of compliance of the simulation results with the actual interannual changes in the AAL of the Black Sea near the considered section of its coast could indeed be significant.

If this assumption is confirmed, the values of Θ may decrease in the coming years. Will this significantly affect the validity of the forecasts under consideration? To answer this question, it is necessary to consider forecasts corresponding to windows for which the values of Θ are maximum and minimum.

As can be seen from Figure 4, during the period under review, values of Θ that are lower than the average level of this indicator (0.71) occurred in the period 2012 – 2016.

The increased values of Θ were for the periods 2008 – 2010. Therefore, as an example, Figure 5 shows the actual changes in the AAL for the hydrometeorological station Sevastopol, corresponding to the windows ending in the specified years (FACT), the results of their modeling (MODEL), as well as their forecasts with a lead time of 1 year.

As follows from Figure 5, in the examples considered, the trends of changes in the forecast of the AAL and the actual changes in these indicators for the hydrometeorological station Sevastopol coincide in 7 cases out of 9. Discrepancies occurred for windows corresponding to the periods 1993 – 2012 and 1995 – 2014. Therefore, all cases when the forecasts under consideration did not come true fall on windows for which the values of Θ were below the average level. No such cases were detected for windows corresponding to Θ>0.8 (all forecasts were justified). Therefore, for the considered windows, the estimate of the feasibility of the proposed forecast is 0.78. The assessment of the feasibility of this forecast, taking into account the results corresponding to all 17 windows, is slightly less and amounts to 13/17.

For the hydrometeorological station Yalta, the estimate of the feasibility of the proposed forecast for the same windows is 0.78, but taking into account all 17 windows, its value was 12/17, which, in our opinion, is quite satisfactory for practical needs. Taking into account the data in Figure 3, it seems likely that for the coming years the validity of the forecasts of the AAL for the same areas of the Black Sea, developed using the described methodology, and taking into account the background of the hydrothermal regime of its basin will remain equally satisfactory. The values of the coefficients, as well as the predictors of the models used to obtain the results shown in Fig. 5, are presented in Table 1.

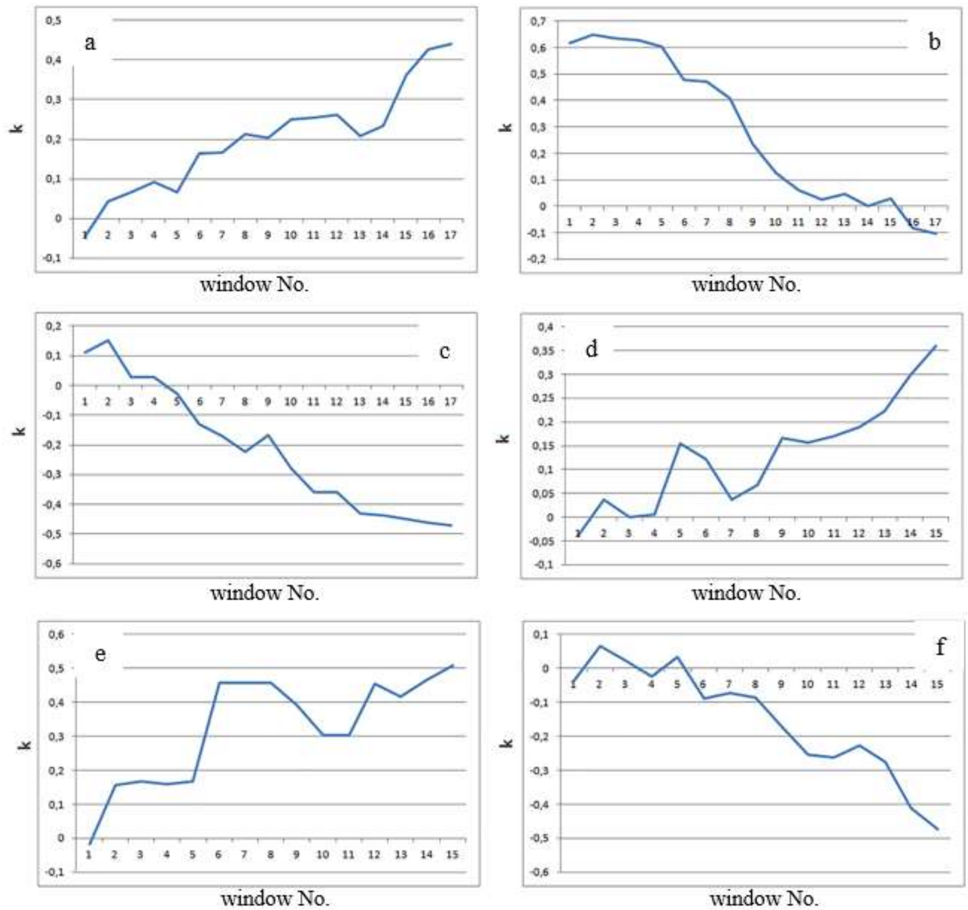

Fig. 3. Examples of the dependence of k on the year of the beginning of the "sliding window" of the AAL , corresponding to the factors used as predictors of the model (1): a) AMAT January, -3; b) AMAT May, -2; c) AMAT July, -5; d) MTP June, -1; e) MTP December, -1; f) MTP August, -2.

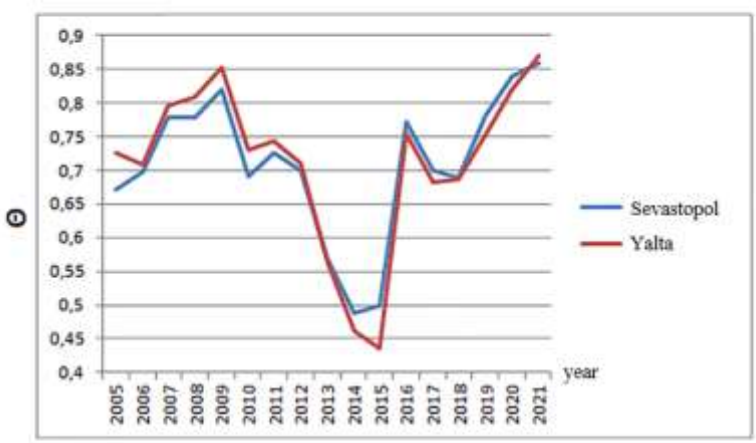

Fig. 4. The dependences of the relative contributions Θ of the results of modeling the interannual changes of the AAL for the hydrometeorological stations Yalta and Sevastopol to their average capacity.

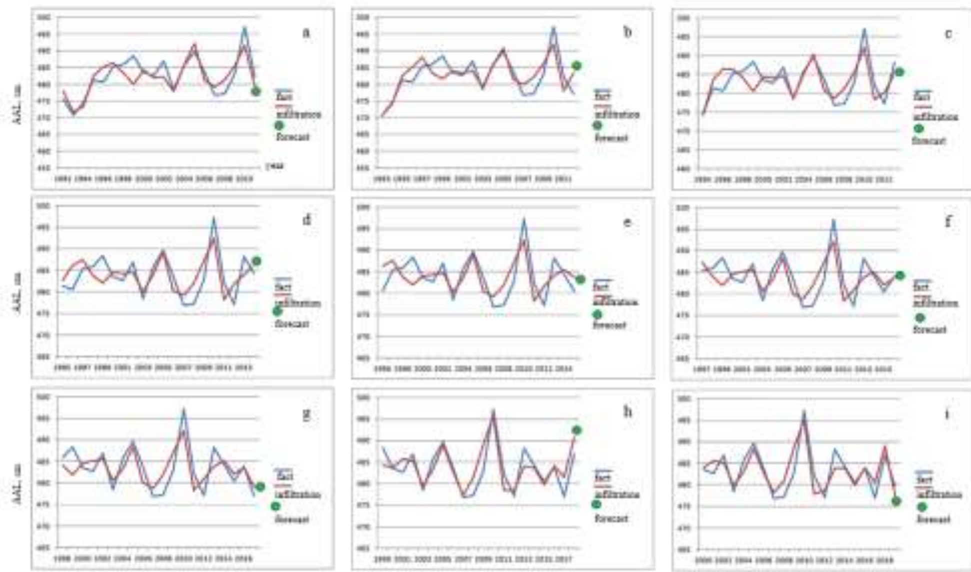

Fig. 5. Depending on the time of the actual values of the AAL of the Black Sea near Sevastopol, the results of their modeling, as well as forecasts with a 1–year lead time, built for the "windows": a) 1992 - 2011; b) 1993 – 2012; c) 1994 – 2013; d) 1995 – 2014; e) 1996 – 2015; f) 1997 – 2016; g) 1998 – 2017; h) 1999 – 2018; i) 2000 – 2019.

Table 1. Coefficients and predictors of models (1) describing changes in the AAL of the Black Sea near Sevastopol for a particular "window".

n	Predictor / Period	C_n								
		1992-2011	1993-2012	1994-2013	1995-2014	1996-2015	1997-2016	1998-2017	1999-2018	2000-2019
0	Free member	-47,05	150.16	403.32	488.84	704.5	-980.9	393.63	624.51	455.66
1	AMAT June,-1	0.471	0.457	0.773	0.722	0.685	5.767	2.551	1.889	0.695
2	AMAT January,-3	0.509	0.658	0.259	0.224	0.221	1.100	0.311	0.131	0.505
3	AMAT May,-2	3.182	3.003	2.920	2.832	2.525	6.083	4.042	3.597	2.776
4	AMAT January,-4	-1,442	-1,068	-1,668	-1,710	-1,622	-2,829	-2,399	-2,321	-1,753
5	AMAT July,-5	-1,354	-1,381	-1,918	-1,983	-2,141	-0.653	-2.431	-2.247	-1.269
6	AMAT August,-5	0.452	-0.501	-0.109	-0.122	-0.441	-4.337	-1.768	-1.557	-0.846
7	MTP June,-1	-0.029	-0.056	0.008	0.022	0.017	-0.251	-0.045	-0.002	0.119
8	MTP December,-1	0.095	0.114	0.098	0.098	0.092	0.319	0.223	0.194	.139
9	MTP August,-2	-0.233	-0.212	-0.273	-0.288	-0.277	-0.855	-0.507	-0.456	-0.563
10	MTP December,-5	-0.083	-0.062	-0.111	-0.123	-0.113	-0.458	-0.275	-0.240	-0.176

As follows from Table 1, the values of the coefficients of the models (1) corresponding to one or another of the considered "windows" differ significantly. The latter indicates that the stationary process of interannual changes in the AAL of the studied area of the Black Sea can be considered only in the zero approximation, and the scenario of the future, which will actually be realized, can only be to some extent close to the "conservative" one.

The scenario of further changes in the factors determining the dynamics of the AAL, which will actually take place, has not been determined. Therefore, from the fact that the developed conservative forecast of the trend of further changes in the AAL of the Black Sea off the Southern Coast of Crimea for the coming year in the period 2014-2023 had a high justification, it does not follow that it is guaranteed to be justified in 2024. However, the probability of such a result is undoubtedly higher than the probability that it will not be justified.

Since the values of Θ for the studied process are on average 0.71, it is obvious that the changes in the hydrothermal regime of the Black Sea catchment basin really made a predominant contribution to the identified trends in the AAL of the Black Sea. As already noted above, there are negative trends in the changes in the values of the AAL of the Black Sea for the hydrometeorological stations Sevastopol and Yalta, predicted taking into account variations in the hydrothermal regime of its basin, as well as in variations in the actual values of this indicator.

The values of the ACLT of the time series of the predicted values of the AAL of the Black Sea in the areas of the hydrometeorological stations under consideration for the observation period under consideration, respectively, are minus 0.63 cm/year and minus 0.52 cm/year (with the actual values of these indicators minus 0.66 cm/year and minus 0.58 cm/year). The reliability of the conclusions of the significance of the identified trends is 0.85, which is relatively small, but significantly more than for the period 2000-2021. Consequently, with further warming of the climate in the Black Sea basin, as well as an increase in its aridity, the identified trends will continue, and the reliability of conclusions about their significance will increase.

It should be noted that the forecast for the coming year, developed using the above methodology, will have a high justifiability only if a conservative scenario (which is one of the likely, but not the only one) is realized. It is not known what this scenario will actually turn out to be, however, as the analysis showed, the proposed forecast in the 21st century is justified in at least 70% of cases. Therefore, it is advisable to use such a forecast as an indicative one.

4 Discussion of results

The results obtained fully correspond to the existing ideas about the patterns of changes in the levels of the inland seas located in the Northern Temperate climate zone [1, 2, 13, 18, 19], the influence of the hydrothermal regime of their catchment areas on them [7, 19], as well as the climate changes taking place in the Black Sea basin in the modern period [5, 21].

The new facts established in this work are:

There are factors of temporal variability of the AAL of the Black Sea off the southern coast of the Crimean Peninsula, whose connections with this process are significantly increasing in the modern period. These include interannual changes in the average indicators of its hydrothermal regime in the catchment area of this sea, which are 1 to 5 years ahead of the predicted process.

The relative contribution of such factors to the average power of the interannual variability of the studied process for 1979 – 2023 averaged 71%, varying from 44% to 87% with a period close to 11 years.

The justifiability of forecasts of the trend of changes in the AAL of the Black Sea in the coming year, near Yalta and Sevastopol, in relation to the year ended, developed using the method of linear multiple regression and taking into account the identified factors, in 2001-2023 exceeds 76%.

The factor that mainly caused the change in the trend of the considered changes in the AAL of the Black Sea is a significant increase in the AMAT for any months in the territory of the Black Sea catchment area. A significant decrease in MTP, identified for the winter months, could also have some impact.

5 Conclusions

Thus, it is established:

1. The linear multiple regression method makes it possible to develop a conservative forecast of the AAL of the Black Sea off the southern coast of Crimea for the coming year, which has satisfactory justification, provided that the factors identified among the indicators of the hydrothermal regime of its catchment area are used as predictors of the corresponding model.
2. The justifiability of such a forecast for the coming year of the trend of the studied process, in relation to the value of this indicator in the previous year, for the period 2001-2023 is close to 70%. Of the 17 developed forecasts, all 13 (for Sevastopol) and 12 (for Yalta) were justified.
3. With further warming, as well as increased aridity of the climate in the Black Sea catchment area, a decrease in the AAL of the sea is likely. This process began in 2010 and is becoming more active in the modern period.

References

1. O. R. Andrianova, *Mnogoletnie kolebaniya urovnya Mirovogo okeana: tendencii i prichiny* (Astroprint, Odessa, 2014)
2. E. Ch. F. Berd, *Izmeneniya beregovoj linii: global. obzor* (Gidrometeoizdat, Leningrad, 1990)
3. S. G. Boguslavskij, A. I. Kubrikov, I. K. Ivanenko, Morskoj gidrofizicheskij zhurnal **3**, 47–57 (1997)
4. E. Yu. Butyrskij, *Metody modelirovaniya i ocenivaniya sluchajnyh velichin i processov* (Strategiya budushchego, SPb., 2020)
5. Vtoroj ocenochnyj doklad Rosgidrometa ob izmeneniyah klimata i ih posledstviyah na territorii Rossijskoj Federacii (Izd-vo Rosgidrometa, 2014)
6. Gidrometeorologiya i gidrohimiya morej SSSR. Tom IV. Chernoe more **1** (Gidrometeoizdat, L., 1991)
7. S. G. Dobrovol'skij, “Izmeneniya klimata i sostavlyayushchih vodnogo balansa”, *Aktual'nye problemy vodoobespecheniya* (Nauka Moskva, 2003)
8. N. Drejper, G. Smit, *Prikladnoj regressionnyj analiz* (Dialektika. M., 2017)
9. Sh. Dzhoashvili, Reki Chernogo morya. – Evropejskoe agenstvo po ohrane okruzhayushchej sredy, Tekhnicheskij otchet **71** (2003)
10. N. N. D'yakov, I. N. Fomina, T. Yu. Timoshenko, A. A. Polozok, Ekologicheskaya bezopasnost' pribrezhnoj i shel'fovoj zon i kompleksnoe ispol'zovanie resursov shel'fa **1**, 62-67 (2016)

11. V. A. Ivanov, V. N. Belokopytov, *Okeanografiya Chernogo morya* (NAN Ukrainy, Morskoj gidrofizicheskij institut, Sevastopol', 2011)
12. Yu. P. Il'in, V. G. Simov, L. N. Repetin, Ekologicheskaya bezopasnost' pribrezhnoj i shel'fovoj zon i kompleksnoe ispol'zovanie resursov shel'fa **22**, 171-181 (2010)
13. R. K. Klige, V. N. Malinin, O. I. Shevchuk, Vestnik Mosk. un-ta. Geografiya **5(1)**, 7–14 (2009)
14. A. E. Lipchenko, L. N. Repetin, Ekologicheskaya bezopasnost' pribrezhnoj i shel'fovoj zon i kompleksnoe ispol'zovanie resursov shel'fa **27**, 249-254 (2013)
15. A. E. Lipchenko, N. N. D'yakov, Trudy GOIN **217**, 241-253 (2016)
16. L. N. Repetin, Yu. P. Il'in, V. V. Dolotov, M. M. Lipchenko, Ekologicheskaya bezopasnost' pribrezhnoj i shel'fovoj zon i kompleksnoe ispol'zovanie resursov shel'fa **18**, 193-204 (2009)
17. V. G. Simov, Naukovi praci Ukraïns'kogo naukovo-doslidnogo gidrometeorologichnogo institutu **266**, 62-69 (2014)
18. I. V. Maksimov, Okeanologiya **11(3)**, 530–541 (1971)
19. V. R. Fuks, Geografiya i sovremennost' **10**, 73–93 (2005)
20. A. V. Holopcev, M. P. Nikiforova, Solnechnaya aktivnost' i prognozy fiziko-geograficheskih processov (Lap lambert Academic Pablishing, 2013)
21. Climate Change: The Physical Science Basis (2013), https://www.ipcc.ch/report/ar5/wg1/lncs, last accessed 2016/11/21.
22. N. N. Dyakov, A. E. Lipchenko, Black Sea Water Balance/ State of the Environment of the Black Sea (2009-2014/5), http://blacksea-commission.org/SoE2009-2014/SoE2009-2014.pdf
23. L. Hoffmann, G. Günther, D. Li, O. Stein et al., Atm. Chem. Phys. **19**, 3097-3124 (2019)
24. V. N. Mikhailov, M. V. Mikhailova The Handbook of Environmental Chemistry **5(Q)**, 91–134 (2008)
25. Bank dannyh ob izmeneniyah meteouslovij v razlichnyh regionah mira, tutiempo.net/climate/.
26. Baza dannyh Rezul'taty reanaliza ERA5 hourly data on pressure levels from 1979 to present, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form