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Original article

Reasons for Rapid Increase of Water Salinity in the Sea of Azov in the 21st Century

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Purpose. When discussing the Sea of Azov salinization both in the 1970s and in the current period, the reduction of river runoff (primarily in the Don River) is indicated as the main reason for this phenomenon that results in the increased advection of the Black Sea waters. However, this factor alone is not enough to explain salinity decrease in the last quarter of the 20th century as well as its rapid growth in 2007–2020. The paper is purposed at assessing the contribution of water balance components to the change in the Azov Sea salinity for more than 50 years (1966–2020).
Methods and Results. A mathematical model of water-salt balance is used to assess the annual average salinity of the Sea of Azov. The variability of all the water balance components and the sources of its uncertainty are considered. It is shown that the model applied is resistant to variation of the input data. Based on the correlation analysis, it is found that during the salinization period, evaporation plays an important role along with the river runoff. At that in the 1970s, a decisive impact upon evaporation was exerted by the wind speed, whereas at the beginning of the 21st century – by the temperature and humidity regimes.
Conclusions. At the beginning of the 21st century, the reason for rapid salinity increase in the Azov Sea waters consisted in the prolonged period of low-water in rivers coinciding with the period of high water and air temperatures that resulted in an increase of evaporation from the sea surface. The obtained results permit to conclude that at the changed atmospheric processes in the region, the only factor consisting in transition from the low river inflows to the Azov Sea basin to the high ones may be not enough to provide significant decrease of seawater salinity. This circumstance should be taken into account when preparing the plans for adapting the economic activities to the climate changes.

Keywords: Sea of Azov, water salinity, water balance, mathematical model, climatic changes, evaporation

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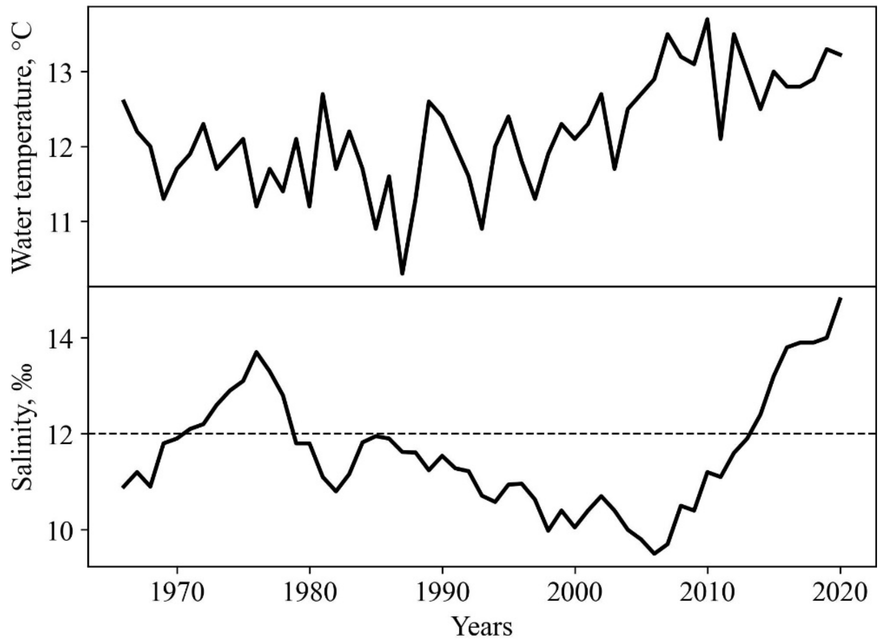
Introduction

Among the oceanographic factors that play an organizing role in the formation of physicochemical and biological image of the Sea of Azov, salinity occupies a leading place, since its changes cause especially rapid and deep deformations of sea most diverse abiotic and biotic components [1].

[1] Bronfman, A.M. and Khlebnikov, E.P., 1985. [*The Sea of Azov: Fundamentals of Reconstruction*]. Leningrad: Gidrometeoizdat, 270 p. (in Russian).

In 2007–2019 the sea ecosystem, based on a set of hydrological indicators, shifted to a state that was not observed during the period of instrumental observations [1]. In the first decade of the 21st century the annual sea-averaged water temperature increased against the background of relatively low water salinity. Then, under low-water conditions in the Don (and then in the Kuban), a rapid increase in salinity began with a slight decrease in the annual average water temperature (Fig. 1).



F i g. 1. Dynamics of annual sea-averaged values of water temperature and salinity in the Sea of Azov

Throughout the entire period of instrumental observations, the annual average salinity of the Sea of Azov waters ranged from 9.3 to 14‰, while the alternation of periods with low (periods of 1924–1935, 1945–1949, 1993–2010), medium (1936–1940, 1950–1971, 1979–1992), and high (1972–1978, 2011 to present) values could be observed.

Salinization periods before the construction and commissioning of the Tsimlyansk Reservoir in 1953 were short, alternating with long fresh phases. However, the next phase of decreased humidity in the basin, which began in the late 1960s, led to extreme salinity values in the Sea of Azov waters in 1972–1978 (up to 13.8‰ in 1976) [2].

The problems of increasing salinity in the Sea of Azov and the coincident drop in the Caspian Sea level attracted much attention; projects for transferring part of the runoff of northern rivers to the Volga and Don basins, construction of structures for regulating water exchange with the Black Sea in the Kerch Strait as well as

[2] Bronfman, A.M., Dubinina, V.G. and Makarova, G.D., 1979. [*Hydrological and Hydrochemical Foundations of the Productivity of the Sea of Azov*]. Moscow: Pischevaya Promyshlennost, 288 p. (in Russian).

between the Taganrog Bay and the central part of the sea – in the Dolgaya Spit area (for example, papers [1, 3] [2]) were discussed and considered.

After 1980, sea salinity began to decline and reached 9.5‰ by 2006. At the same time, the Caspian Sea level began to rise [3]. Thus, the problems outlined above resolved themselves; the work on projects for transferring the runoff of northern rivers to the south was curtailed in 1986. Simultaneously, expeditionary research programs in the Sea of Azov were reduced sharply [4].

The long-term freshening of the Sea of Azov (1979–2006) was explained by the periodicity in the long-term fluctuations of atmospheric circulation [5, 6].

In 2007, there was a sharp change in the sea salinity dynamics and a new period of salinization began. Starting from a very low value (less than 10‰), salinity continuously increased exceeding 14‰ in 2020 [7], which is a historical maximum.

When studying the causes of sea salinization in 1972–1978, the main emphasis was on reducing river runoff, the deficit of which was compensated by the inflow of the Black Sea waters. At the same time, the authors of [8, p. 110], referring to monograph [1] note that "a feature of the Sea of Azov water balance is the secondary importance of moisture exchange with the atmosphere and significant dependence of the incoming and outgoing parts of the balance on water exchange with the Black Sea and anthropogenic transformation of river runoff into the sea". When discussing the sea salinization after 2007, a reduction in river runoff, primarily of the Don, and increased advection of the Black Sea waters [7, 9] are also indicated as its main causes.

This work is aimed at considering the contribution of all water balance components to changes in the Sea of Azov salinity for more than 50 years (1966–2020). This choice of the study period is due to the fact that this time period, firstly, is most fully provided with data from continuous observations at coastal hydrometeorological stations, and secondly, it covers both periods of the strong Sea of Azov salinization.

Materials and methods

The material for the study is a publicly available oceanographic database for the Sea of Azov for 1924–2012 [10, 11] supplemented by the expeditionary work results of Southern Scientific Center of RAS for 2013–2020 [12, 13]. The annual sea-averaged salinity values were calculated according to [14].

The sources of the data from long-term coastal observations at marine hydrometeorological stations (HMS) of the Sea of Azov were the Unified State Information System on the World Ocean (ESIMO [4]) and a publicly available database RIHMI-WDC [5]. We used information on temperature and relative humidity, wind speed, precipitation, water temperature and sea level.

[3] Vorovich, I.I., ed., 1981. [*Rational Use of Water Resources in the Azov Sea Basin: Mathematical Models*]. Moscow: Nauka, 360 p. (in Russian).

[4] ESIMO. *The Unified State Information System on the World Ocean*. 2023. [online] Available at: http://portal.esimo.ru/portal [Accessed: 24 March 2022] (in Russian).

[5] RIHMI-WDC. *The Unified State Data Fund*. Available at: http://meteo.ru [Accessed: 29 March 2022] (in Russian).

The work uses the data from the State Water Cadastre publications on daily water discharge at the following gauges: Razdorskaya (the Don), Tikhovsky, Zaitsevo Koleno (the Kuban) and Slobodka (the Protoka branch).

Mathematical model of the Sea of Azov water and salt balance

To calculate the water balance, the following mathematical model is considered:

$$\Delta V(t+1,t) = V(t+1) - V(t) = Sq \cdot \Delta h(t+1,t) = Q_{riv} + Q_{prec} + Q_{BA} - Q_{eva} - Q_{AB}\,, \quad (1)$$

where $\Delta V(t+1, t)$ is sea volume variation, km^3/year; $V(t+1)$ is the Sea of Azov volume at the end of the year t, km^3; $V(t)$ is the Sea of Azov volume at the beginning of the year t, km^3; t is number of the year; Sq is the Sea of Azov area, 38 thousand km^2 [15]; $\Delta h(t+1, t)$ is average sea level variation, m/year; Q_{riv} is inflow of river waters, km^3/year; Q_{prec} is precipitation on the water area, km^3/year; Q_{eva} is evaporation, km^3/year; Q_{BA} is water inflow from the Black Sea, km^3/year; Q_{AB} is water outflow into the Sea of Azov, km^3/year. All the flows are specified in the interval from t to $t+1$.

Water exchange between the Sea of Azov and Sivash Bay is not considered.

The average annual salinity of the Sea of Azov is assessed on the basis of a salt balance model:

$$M(t+1) = M(t) + S_B \cdot Q_{BA} - k \cdot S(t+1) \cdot Q_{AB}\,,$$

$$M(t) = S(t) \cdot V(t)\,,$$

$$S(t+1) = \frac{M(t+1)}{V(t+1)} = \left(\frac{S(t) \cdot V(t) + S_B \cdot Q_{BA}}{V(t+1) + k \cdot Q_{AB}}\right), \quad (2)$$

$$S_A = \frac{S(t+1) + S(t)}{2}\,,$$

where $M(t+1)$ is weight of the salt in the Sea of Azov at the end of the year, mln tons; $M(t)$ is weight of the salt in the Sea of Azov at the beginning of the year, mln tons; $S(t+1)$ is average sea salinity at the end of the year, ‰; $S(t)$ is average sea salinity at the beginning of the year, ‰; S_B is salinity of the Black Sea waters, ‰; k is parameter reflecting the fact that the water outflowing from the Sea of Azov into the Black Sea has a salinity greater than the average value for the sea; S_A is annual average salinity of the Sea of Azov, ‰.

The salinity of the Black Sea water masses entering the Sea of Azov is assumed to be 18‰. The k parameter was considered as a calibration parameter.

In the salt balance equation (2), the exchange with Sivash Bay is also not taken into account.

The following approach was adopted to assess the interannual dynamics of the Sea of Azov level Δh for the period under consideration (1966–2020). The average annual values were calculated for each coastal HMS provided with sea level measurement data. Next, averaging over all HMS was performed and an estimate of the average sea level in each year was obtained.

The fresh water inflow into the Sea of Azov is determined mainly by the runoff of the Don and Kuban rivers (about 95%). To estimate the annual river water runoff into the sea, we used observational data on water discharge in Razdorskaya gauge (outlet section on the Don River, 1966–2020) and Tikhovsky gauge (located in front of the head of the Kuban River delta and the separation of the Protoka branch, 1966–2005). In 2006, at the head of the Kuban River delta, the Tikhovsky low-pressure hydropower complex was constructed. It artificially distributes the Kuban River runoff between the Kuban and Protoka branches as well as the main canal of Petrovsko-Anastasievskaya irrigation system. Therefore, for the period of 2006–2020, we used the sum of water discharges as the Kuban runoff at two gauges: Zaitsevo Koleno (the Kuban branch) and Slobodka (the Protoka branch). When calculating the total annual river runoff, lateral inflow and water consumption in areas downstream from the indicated sections of the Don and Kuban rivers are not taken into account. The data on the annual runoff of small rivers into the Sea of Azov for 1966–1985 were taken from [16], for the subsequent period we used 1.5 km^3/year value.

To calculate atmospheric precipitation, we used observational data from four coastal HMS: Taganrog, Primorsko-Akhtarsk, Genichesk and Kerch. Currently, some work is carried out on refining the methodology for calculating precipitation falling on the Sea of Azov water area according to coastal HMS data and satellite radar images [17]. However, for the period under consideration such a series is not available. The values of the total annual precipitation layer from four coastal HMS were averaged to calculate the average annual precipitation layer over the sea. The precipitation volume is obtained by multiplying this value by the sea surface area.

To calculate evaporation from the Sea of Azov water surface, we used some recommendations [6] and the following formula:

$$q_{\text{eva}} = 0.14 \cdot n \cdot (e(T_w) - f \cdot e(T_a)) \cdot (1 + 0.72 \cdot U), \tag{3}$$

where q_{eva} is evaporation from the water surface, mm/month; n is number of days in a month; $e(T_w)$ is saturated water vapor pressure at 2 m height from the water surface at water temperature T_w, hPa; $e(T_a)$ is saturated water vapor pressure at 2 m height from the water surface at air temperature T_a, hPa; f is relative humidity; U is wind speed at 2 m height from the water surface, m/s.

The pressure of the saturated water vapor is calculated by T (°C) temperature using the Magnus formula:

$$e(T) = 6.1 \cdot 10^{\frac{7.45 \cdot T}{(235 + T)}}.$$

The average daily values of water and air temperature, wind speed, and relative humidity for the whole sea were calculated using the data from six coastal HMS: Taganrog, Yeisk, Primorsko-Akhtarsk, Kubanskaya Ustevaya, Genichesk and Berdyansk – in accordance with the approach proposed in [18]. Then $e(T_a)$ and $e(T_w)$ values were calculated and averaged within a month. Taking into account the monthly average relative humidity, the evaporation per month using formula (3) were calculated. Annual evaporation was summed for months when ice cover was

[6] Kuznetsov, V.I., Golubev, V.S. and Fedorova, T.G., 1969. [*Guidelines for Calculating Evaporation from the Surface of Water Bodies*]. Leningrad: Gidrometeoizdat, 84 p. (in Russian).

absent. Thus, when assessing evaporation, the winter months were not taken into account as well as some recommendations from the paper [6] related to wind speed and air humidity transformation above the water surface.

The calculation of water exchange with the Black Sea through the Kerch Strait was carried out using the formulas substantiated in [16, p. 99]:

$$Q_{BA} = \frac{42.6}{1.014^{F}}, \quad Q_{AB} = 41.4 \cdot 1.01^{F}, \tag{4}$$

where $F = Q_{\text{riv}} + Q_{\text{prec}} - Q_{\text{eva}}$.

In addition, the water outflow into the Black Sea Q_{AB} was additionally assessed using the water balance equation (1):

$$Q_{AB} = Q_{\text{riv}} + Q_{\text{prec}} + Q_{BA} - Q_{\text{eva}} - \Delta V(t+1, t). \tag{5}$$

To take into account some existing errors in assessing the components of the Sea of Azov water balance (which will be described in more detail below), the following scheme of computational experiments is considered.

Noise is added to the values of the water balance components of the basic calculation option (Table) according to the following rule:

$$Q = Q + Q \cdot \xi \cdot cv = Q \cdot (1 + \xi \cdot cv),$$

where Q is one of the variable components of the water balance (precipitation, river runoff, evaporation, water inflow from the Black Sea, variation of the sea volume); cv is variation coefficient of the water balance corresponding component; ξ is random variable uniformly distributed over the interval of (− 0.5; + 0.5).

The result is a new data set where the water balance components deviate from the base case in one direction by no more than a half of the variation coefficient calculated from the original series. Using model (2), the dynamics of average sea salinity in 1966–2020 was obtained. At the same time, to maintain the water balance, the water outflow from the Sea of Azov Q_{AB} is determined by equation (5).

A total of 1000 generations of the dynamics of water balance components was performed. The average, maximum and minimum values for the average sea salinity were calculated based on the results of this series of experiments.

We used correlation analysis to assess the relationship between the water balance components as well as the factors that determine them and the Sea of Azov salinity. The sample Pearson correlation coefficient was calculated for pairs of annual time series and its statistical significance was determined. The correlation coefficients were calculated within a sliding window of a specified size to examine changes in these relationships over time.

The window size should not be too small, since the series under consideration will be too short and it will affect the value and significance of the correlation coefficient. On the other hand, the window size is limited from above by the length of the original series (in our case, this is 55 annual values from 1966 to 2020). The final window size is chosen to be approximately a half of the original series: 30 years. Thus, the correlation analysis is first performed for the period of 1966–1995, then for 1967–1996, etc., until 1991–2020.

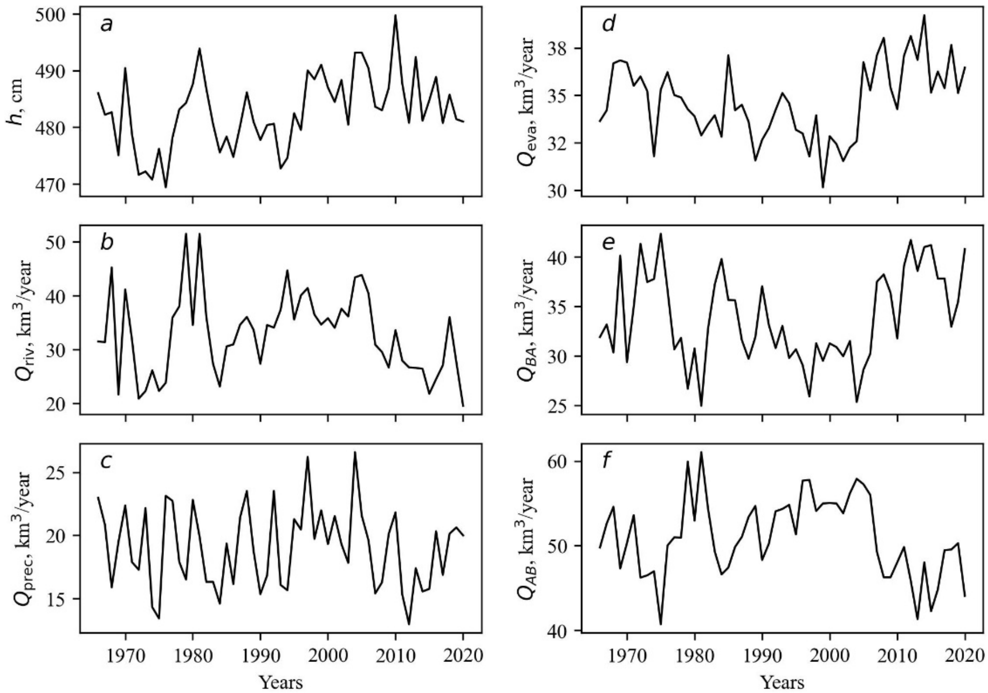
Changes of water balance components (km^3/year) and average salinity (‰) S of the Sea of Azov based on the results of modeling and field observations S_{obs} [1]

Year	ΔV	Q_{riv}	Q_{prec}	Q_{eva}	Q_{BA}	Q_{AB}	S_{obs}	S
1966	2.9	31.5	23.0	33.6	31.9	49.8	10.9	10.9
1967	−1.4	31.4	20.8	34.2	33.2	52.6	11.2	11.0
1968	0.2	45.2	15.9	36.7	30.3	54.6	10.9	10.7
1969	−2.9	21.7	19.5	36.8	40.1	47.3	11.8	11.4
1970	5.8	41.1	22.4	36.7	29.4	50.3	11.9	11.0
1971	−4.4	31.8	17.9	35.5	35.0	53.6	12.1	11.2
1972	−2.7	20.9	17.3	36.0	41.3	46.2	12.2	11.9
1973	0.2	22.3	22.2	35.2	37.5	46.5	12.6	12.2
1974	−0.5	26.1	14.3	31.8	37.8	47.0	12.9	12.4
1975	2.1	22.3	13.4	35.3	42.3	40.7	13.1	13.0
1976	−2.6	23.8	23.1	36.2	36.7	50.0	13.7	13.1
1977	3.3	35.9	22.7	35.0	30.7	51.0	13.3	12.6
1978	1.9	38.0	17.9	34.9	31.8	50.9	12.8	12.2
1979	0.4	51.5	16.5	34.3	26.7	59.9	11.8	11.4
1980	1.2	34.5	22.8	33.9	30.8	52.9	11.8	11.2
1981	2.4	51.5	19.9	32.9	25.0	61.0	11.1	10.4
1982	−2.7	36.1	16.3	33.5	32.7	54.4	10.8	10.5
1983	−2.4	27.3	16.3	34.0	37.2	49.3	11.2	10.9
1984	−1.9	23.1	14.6	32.8	39.8	46.6	11.8	11.5
1985	1.1	30.6	19.4	37.1	35.6	47.4	12.0	11.7
1986	−1.4	31.0	16.1	34.2	35.6	49.9	11.9	11.8
1987	2.1	34.6	21.4	34.5	31.6	51.0	11.6	11.6
1988	2.3	36.0	23.5	33.6	29.7	53.4	11.6	11.2
1989	−2.0	33.6	18.8	31.6	31.9	54.7	11.2	11.1
1990	−1.2	27.4	15.3	32.7	37.0	48.3	11.5	11.5
1991	1.0	34.5	16.8	33.3	33.1	50.2	11.3	11.4
1992	0.1	34.1	23.5	34.2	30.8	54.1	11.2	11.2
1993	−3.0	37.4	16.1	35.1	33.0	54.3	10.7	11.2
1994	0.7	44.7	15.7	34.6	29.8	54.8	10.6	10.9
1995	3.0	35.6	21.3	33.2	30.7	51.3	10.9	10.7
1996	−1.1	40.0	20.5	33.0	29.1	57.7	11.0	10.4
1997	4.0	41.4	26.2	31.8	25.9	57.8	10.6	9.9
1998	−0.6	36.5	19.7	34.0	31.3	54.1	10.0	9.9
1999	1.0	34.6	22.0	30.2	29.5	55.0	10.4	9.8
2000	−1.5	35.8	19.3	32.9	31.3	55.0	10.1	9.8
2001	−1.0	34.0	21.5	32.4	30.9	55.0	10.4	9.8
2002	1.5	37.6	19.3	31.5	30.0	53.8	10.7	9.8
2003	−3.0	36.1	17.8	32.3	31.5	56.2	10.4	9.8
2004	4.8	43.4	26.6	32.6	25.3	57.9	10.0	9.3
2005	0.0	43.8	21.6	36.8	28.6	57.3	9.8	9.2
2006	−1.1	40.4	19.6	35.3	30.2	56.0	9.5	9.3
2007	−2.6	30.9	15.4	37.1	37.5	49.2	9.7	9.9
2008	−0.2	29.5	16.3	38.0	38.2	46.3	10.5	10.5
2009	1.5	26.7	20.1	35.4	36.4	46.2	10.4	10.9
2010	4.9	33.6	21.8	34.3	31.8	48.0	11.2	10.8
2011	−4.6	27.9	15.3	37.1	39.1	49.8	11.1	11.4
2012	−2.6	26.7	13.0	38.1	41.7	45.9	11.6	12.0
2013	4.4	26.6	17.4	36.9	38.6	41.3	11.9	12.4
2014	−4.3	26.4	15.6	39.2	41.0	48.0	12.4	12.9
2015	1.4	21.8	15.8	35.1	41.2	42.2	13.2	13.3
2016	1.6	24.5	20.3	36.3	37.8	44.8	13.8	13.4
2017	−3.1	27.1	16.9	35.4	37.8	49.5	13.9	13.5
2018	1.9	36.0	20.1	37.7	32.9	49.5	13.9	13.2
2019	−1.6	27.7	20.6	35.1	35.5	50.3	14.0	13.1
2020	−0.2	19.6	20.0	36.5	40.8	44.1	14.8	13.5

The result of this procedure was displayed on a graph of the correlation coefficient variation over time with a mark of its significance for a specific period. The coefficient value on the graph is related to the end of the period, i.e., each point is read as a characteristic of relationship between two factors over the previous 30 years. The significance level for the analysis was chosen to be 0.05.

Results and discussion

Level variation and volume of the Sea of Azov. From 1993 to 2021, the average water level in most of the World Ocean increased (see the map presented in [19, p. 11]); in some ocean basins it rose by 15–20 cm. At the same time, the "transfer" of the World Ocean water level variations into inland seas is quite complex and insufficiently studied, since knowledge about the water balance of the seas is limited and the water exchange between some seas and oceans has not been quantified [20]. At the same time, the eustatic rise of the Sea of Azov level in the second half of the 20th century is estimated at 2 mm/year.



F i g. 2. Dynamics of the Azov Sea level (a) and the components of its water balance: river discharge Q_{riv} (b), precipitation Q_{prec} (c), evaporation Q_{eva} (d), water inflow from the Black Sea Q_{BA} (e), and water outflow to the Black Sea Q_{AB} (f)

If we compare the Sea of Azov level at the beginning of the 20th century, according to measurements at HMS, with its current position in the first decades of the 21st century, the difference is approximately 15 cm (Fig. 2, *a*). To assess how accurate this assessment is, a separate study that is beyond the scope of this paper is required. At the same time, changes in sea volume can be assessed and used in calculations (Table). According to our estimates, the annual sea volume change in 1966–2020 varies from – 4.6 to 5.8 km^3. As a rule, after a sharp increase in sea volume, the next year is followed by a similar decrease (for example, 1970–1971, 2010–2011, 2013–2014 in the Table). In this case, the average volume variation is close to zero. This confirms the opinion of the authors of [20] that the water balance of marginal seas greatly affects variations in their level and trends caused by the World Ocean level variations cannot be directly extrapolated to the Sea of Azov.

River runoff. Since 2007, a long period of low water on the lower Don, interrupted by a spring flood in 2018, has been observed. Moreover, in 2019, problems with water supply were already noted both in the Don and in the Kuban basin. At the same time, in 2007–2020, the volume of fresh water inflowing the sea was on average approximately the same as in the previous salinization period (1972–1978). However, the current low-water period is longer (Table, Fig. 2, *b*). It should be noted that in the period from 1978 to 2006, when the Sea of Azov salinity decreased, strong increase in river runoff was absent (it reached high values ~ 51 km^3/year (in 1979 and 1981) only twice with an average value of 36.7 km^3 /year). At the same time, in 2018, which was the most water-rich year since 2006, the runoff amounted to 36.0 km^3/year.

Precipitation. Atmospheric precipitation is the most important factor in the formation of river runoff and water balance in the Sea of Azov and the most controversial characteristic of climate variability. As a result of climate change at the end of the 20th – beginning of the 21st centuries, an increase in the annual amount of precipitation relative to the first half of the 21st century (on the western and southern coasts of the sea by about 130 mm, on the eastern – about 70 mm) with an increase in the variability of their amount from year to year [21], was noted. A positive trend of atmospheric precipitation during 1891–1995 is presented in [22]. According to the authors of [23], annual precipitation increased by 54 mm from 1979 to 2010. Currently, a positive trend in the south of Russia continues for the spring season with a decrease in precipitation in the summer [7]. After 2010, there has been a slight decrease in annual precipitation (especially in the east) on the Sea of Azov coast mainly due to a decrease in its amount in summer and autumn [21] (Table, Fig. 2, *c*).

Atmospheric precipitation variability is significantly less than that of continental runoff and is determined to a greater extent by cyclic variations in global atmospheric circulation [5, 24]. It is noted that "the amplitude of interannual precipitation fluctuations is 11.0–14.4 km^3, σ = 2.8–2.9 km^3" [8, p. 122]. During the period under consideration the calculated annual precipitation volumes ranged from 13.0 to 26.6 km^3, σ = 3.2 km^3, median is 19.3 km^3 (Table). Moreover, in 2007–2020, less precipitation fell on the sea area than before – on average 17.8 (13.0–21.8) km^3/year. During the first period of sea salinization, an average of 18.7 (13.4–23.1) km^3/year was obtained.

According to the authors of [8, p. 122] with reference to [25], "taking into account small size of the sea and the dense, relatively uniform observation network, the interpolation error in determining precipitation that fell on the surface of the Sea of Azov should not be high, especially in years when cyclonic genesis of precipitation prevails. Taking into consideration the errors in precipitation measurements, which are mainly eliminated by introducing appropriate corrections, as well as errors in spatial

[7] Rosgidromet, 2019. *A Report on Climate Features on the Territory of the Russian Federation in 2018*. Moscow: Rosgidromet, 79 p. (in Russian).

interpolation, the error in estimating annual average precipitation amounts (with 67% probability) to 1.15 km^3 or 8%."

Evaporation. The work [8, p. 122–123] notes that "significant complexity of determining water exchange through the straits does not enable us to find evaporation as a residual term in the water balance equation." At the same time, the error in determining the annual average evaporation values based on semi-empirical formulas is estimated at 1.35 km^3. In the amount of evaporation for 1923–2000 [8], we note a decreasing trend, which is explained by regional features of climate change in the last 30 years, associated with a decrease in the average wind speed over the Sea of Azov [26] and an increase in cloudiness in summer [8, p. 123].

The calculated volume of evaporation from the Sea of Azov surface is presented in the Table and in Fig. 2, *d*. When comparing the calculated values with the data presented in the tables of the Sea of Azov water balance [16] for 1966–1985, one can see that the average value of evaporation according to calculations is higher by 1.3 km^3/year (34.7 versus 33.4 km^3/year), varies from 30.2 to 39.2 km^3/year versus 25.8–36.8 km^3/year, the amplitude of interannual fluctuations is 1.5 times smaller, and so is the standard deviation. These differences are associated with a sharp decrease in evaporation, presented in the monograph [16], in 1977–1980.

A negative evaporation trend has been traced since the early 1980s until the end of the 20th century. This is due to a wind speed decrease in the Sea of Azov region. Since the beginning of the 21st century, while the wind speed remained low, evaporation began to rise and increased from 32 to 38 km^3/year by 2011–2012 (Table and Fig. 2, *d*) due to an increase in air temperature, water temperature, and a sharp decrease in relative air humidity.

It should be noted that calculation of evaporation according to formula (3) using coastal HMS data leads to errors. Their assessment (for example, in [27]) provides values equal to ~ 20–25%, usually towards underestimating the amount of evaporation over a water body. Indirect methods are used to correct these systematic errors. For example, in [16] it is assumed that in the open sea evaporation is proportional to its values in the coastal zone and can be determined through modular coefficients (the ratio of the annual average values to the long-term average). The long-term average value in the open sea is calculated from archival ship observations. However, due to the small volume of modern synchronous ship observations, it is difficult to update the long-term average value in the open sea. According to calculations, for the period under consideration it amounted to 34.7 km^3/year, which almost coincides with the value of 34.6 km^3/year indicated in [16] as the average for 1923–1985. Therefore, the use of modular coefficients relative to this average will hardly change the results. In addition, reanalyses can be used to estimate evaporation in the open sea, but in this work only direct measurement data were considered to prepare the input information.

Water exchange through the Kerch Strait. In [8], a detailed analysis of methods and approaches to assess the water exchange values in the Sea of Azov and the Black Sea as well as the difficulties associated with this was carried out. As an example, we can note the fact that in 1991 two reference books on the Sea of Azov [16] and the Black Sea [28], edited by FSBSI "SOI" specialists, were published. Both reference books contain tables of water balance of the corresponding water bodies for 1924–1985. At the same time, the volumes of water flows from the Sea of Azov to the Black Sea and backwards significantly differ in these two publications. If we compare the volumes of water inflow into the Sea of Azov for 1966–1985, presented in these reference books, we get 38.0 (27.1–47.5) and 33.3 (28.9–39.8) km^3/year, respectively, i.e., on average, the Black Sea reference book underestimates the inflow of the Black Sea waters by 4.7 km^3/year. Accordingly, the water outflow into the Black Sea is overestimated by approximately the same amount: 46.6 (35.2–71.2) versus 50.6 (41.8–68.9) km^3/year. This is due to different empirical formulas adopted for calculating water exchange through the Kerch Strait.

When comparing methods for calculating water exchange through the Kerch Strait according to [16] and [28], it was found that the calculation of water outflow into the Black Sea using the formulas from both reference books leads to approximately the same values. The calculation of water inflow from the Black Sea using the formulas from [28] has very low variability. Thus, the root-mean-square deviation for the period of 1966–2020 for the water outflow into the Black Sea according to [16] and [28] was 4.83 and 4.80 km^3/year, respectively, and for the water inflow from the Black Sea – 4.57 and 0.91 km^3/year. There is no reason to believe that the same conditions of water movement in the strait provide high interannual variability in the water outflow into the Black Sea, while maintaining low variability in the water inflow into the Sea of Azov. Therefore, formulas (4) adopted in this work for calculating water exchange through the strait correspond to the reference book [16] for the period of regulated runoff. With their help, the inflow of water masses from the Black Sea was computated, and the water outflow from the Sea of Azov was calculated using the water balance equation (5) (table, Fig. 2, *e – f*).

If we compare two salinization periods (1972–1978 and 2007–2020), the inflow of the Black Sea waters is approximately the same: 40.3 (35.4–48.0) and 41.0 (35.4–45.3) km^3/year, respectively. Therefore, an increased advection of water from the Black Sea in response to changes in the freshwater balance cannot be the only cause for such a rapid salinity increase in contemporary times. During the long period of desalination (1979–2006), the inflow of the Black Sea water was on average 6 km^3/year less, while maintaining interannual variability of 34.3 (27.7–42.5) km^3/year.

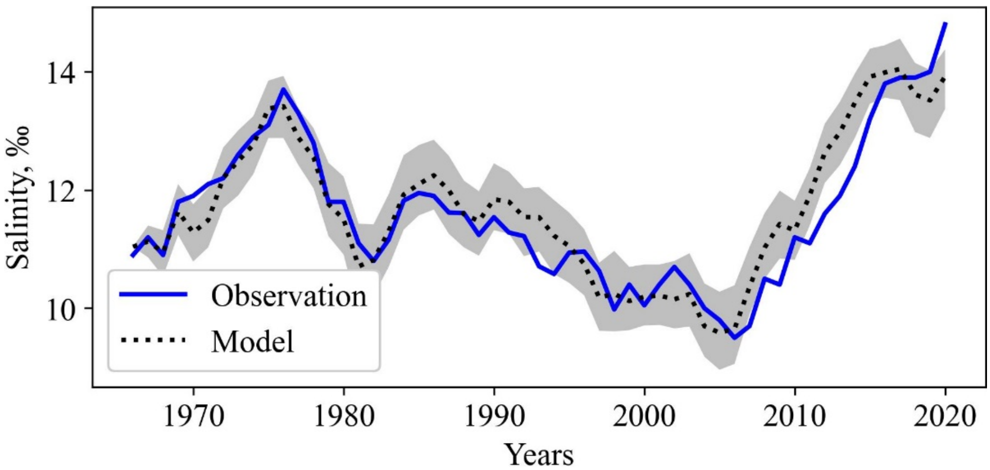
The recently published work [29] presents estimates of the outflow of water from the Sea of Azov for 1981–2019, which were obtained using a new approach based on satellite data (see description of the method in [30]). According to the authors of this paper, formation of water exchange through the strait is mainly associated with local hydrometeorological processes.

We compared the estimates of annual outflow of the Sea of Azov waters into the Black Sea presented in the paper with those calculated in this work. With close average values, there are significant differences in the interannual variability: 56.0 (28.0–82.0) km^3/year in [29] versus 55.3 (45.7–63.9) km^3/year in the present work; the root-mean-square deviation is more than three times greater – 13.1 versus 4.2 km^3/year. However, if we use the volumes of water inflowing the Black Sea according to the data from [29] in the water balance equation (5), then sometimes extremely small and extremely large volumes of compensatory inflow of the Black Sea waters appear (for example, 5.2 km^3/year in 1989, 4.4 km^3/year in 2004, 62.2 km^3/year in 1984, 65.4 km^3/year in 2018), which have not been noted in the literature before. There is no physical explanation for such a strong interannual variation in water exchange.

Dynamics of average sea salinity. The calculated annual average salinity over the sea area in comparison to S_{obs} estimates obtained as a result of observational data averaging [1] is presented in the Table. The calibration parameter κ equal to 1.04 was applied in the calculations. In general, model (1)–(2) reconstructs the observed change in average sea salinity, an increase in salinity during the first salinization period, a subsequent decrease in sea salinity from 1976 to 2006 and a rapid increase in salinity from 2007 to the present date.

The modeling results reveal that the salinity increase in 2007–2020 is associated not only with a prolonged low-water period on the Don, but also with climatic processes: warming, increased moisture deficiency in the region and, as a consequence, increased evaporation from the water surface. It is of interest that the evaporation increase in the region is also noted by the authors of the work [8], who presented the water balance of the Tsimlyansk Reservoir from 2000 to 2018. Thus, evaporation from the reservoir water area increased from 2130 to 2780 mln m^3/year, i.e., by 30%, despite the fact that in some years, due to insufficient filling of the reservoir, its surface area was reduced.

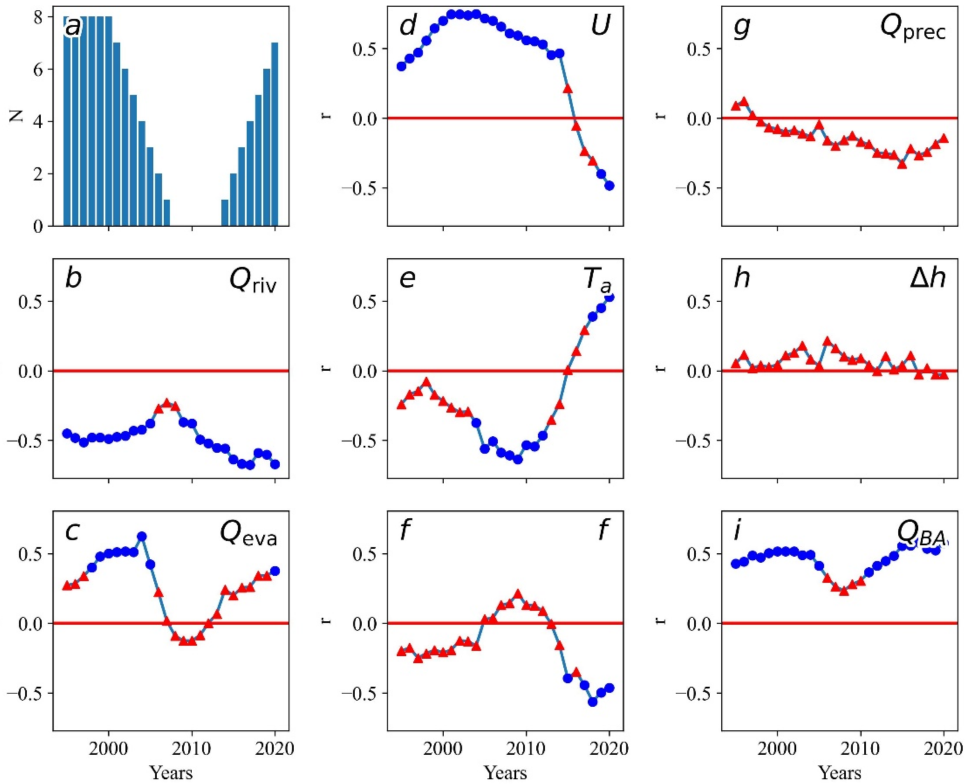
Fig. 3 presents the results of a series of computational experiments calculating the average sea salinity with the addition of random errors to the water balance components. It can be seen that model (1)–(2) reflects variability of the salinity regime and maintains the main trends when external factors vary. This enables us to speak about the validity of the conclusions obtained even when using other methods for determining the elements of water balance different from those used in this work, if the difference between them fits within the magnitude of the specified errors.



F i g. 3. Comparison of the sea-averaged salinity of the Sea of Azov based on observations [1] with the results of a series of experiments (line corresponds to the average value, gray area – to the range of values from minimum to maximum ones)

[8] Georgievsky, V.Yu., ed., 2020. [*Scientific and Applied Handbook: Main Hydrological Characteristics of Water Bodies of the Don River Basin*]. St. Petersburg: Svoye Izdatel'stvo, 262 p. (in Russian).

To facilitate the interpretation of the correlation analysis results and graphs of changes in correlation coefficients over time, a histogram of number of high-salinity years (more than 12‰) falling within the corresponding sliding window was constructed (Fig. 4, *a*). This enables us to determine how strongly a particular point on the time graph of correlation coefficients characterizes high-salinity period. Three periods can be distinguished: I) sliding windows capturing the years of salinization in the 1970s; II) windows covering subsequent years of sea desalination, and III) windows containing years of salinization at the beginning of the 21st century.



F i g. 4. Histogram of a number of years *N* with high salinity in the Sea of Azov (more than 12‰) that fell into the corresponding sliding window (*a*), and dynamics of variation of the correlation coefficients *r* between salinity and the following characteristics: river discharge Q_{riv} (*b*); evaporation Q_{eva} (*c*), wind speed *U* (*d*), air temperature T_a (*e*), relative humidity *f* (*f*), precipitation Q_{prec} (*g*), change of sea level Δh (*h*) and water inflow from the Black Sea Q_{BA} (*i*). Statistically significant correlation coefficients are marked with blue circles, insignificant ones – with red triangles

In the first period, there is a significant negative correlation between sea salinity and river runoff (Fig. 4, *b*) and a significant positive correlation with evaporation (Fig. 4, *c*) and wind speed (Fig. 4, *d*). Moreover, by the beginning of the salinization period in the 1970s there is an increase in the absolute values of the correlation coefficients of all three of these parameters and by the end of this period there is a decrease in them. In addition, the amplitude of changes in the correlation coefficient for river runoff is small, but for evaporation and wind speed it is significant.

In the second period corresponding to sea freshening, the correlation with river runoff (Fig. 4, *b*) and evaporation (Fig. 4, *c*) ceases to be significant. At the same time, a fairly strong positive relationship with wind speed remains (Fig. 4, *d*) and a negative relationship with air and water temperatures becomes significant (Fig. 4, *e* shows only the air temperature graph, since the water temperature graph copies it almost entirely).

In the third, contemporary period of salinization, the significance of relationship between salinity and river runoff is reconstructed (Fig. 4, *b*), while the absolute values of the correlation coefficient are slightly higher than in the first period. At the end of the third period, when more and more high-salinity years fall into the sliding window, the relationship with wind speed (Fig. 4, *d*) and air/water temperature (Fig. 4, *e*) becomes significant, but the sign of the relationship for these dependencies changes to the opposite compared to previous periods. Additionally, a significant negative relationship with relative humidity occurs (Fig. 4, *f*) and the importance of evaporation begins to increase (Fig. 4, *c*).

As for other water balance components, the correlation between the Sea of Azov salinity and precipitation (Fig. 4, *g*), as well as sea level changes (Fig. 4, *h*), is always low and insignificant.

By virtue of formulas (4), the flows of water exchange with the Black Sea functionally depend on the river runoff, therefore the shape of the graphs and the values of the correlation coefficients are repeated almost up to the sign. Fig. 4, *i* shows a graph of the Black Sea water inflow and a graph of the Sea of Azov water outflow, which is almost completely identical to the river runoff graph (Fig. 4, *b*).

As a result of analysis, it was found that the Sea of Azov salinity is strongly related to the amount of river runoff during salinization periods, while during the desalinization phase this relationship weakens. In both periods of salinization, evaporation also plays an important role, with the difference that in the first period the determining effect was the wind speed and in the second – the temperature and humidity regime.

Thus, the high rate of increase in the Sea of Azov water salinity at the beginning of the 21^{st} century can be explained by two factors. Firstly, it was a long low-water period when the water shortage of the current year was gradually aggravated by the accumulating deficit of previous years. Secondly, the increased temperature background observed at the same time led to an increase in evaporation from the water surface. A detailed assessment of the role of these two factors requires additional research.

There is less clarity regarding the main driving factors during the desalination period: it is clear that the role of both river runoff and evaporation was reduced. At the same time, the relationship between salinity and wind speed as well as air/water temperature remains high. Since during this period the direct correlation with evaporation is weak, it cannot be reliably stated that wind and temperature affect salinity through it. The small impact of evaporation during the desalination period can be explained by multidirectional effects of the factors determining it, which compensate each other (for example, a drop in wind speed led to a decrease in evaporation and a temperature rise led to its increase).

In addition, it can be assumed that the negative relationship between sea salinity and temperature is random, reflecting the fact that the period of salinity decrease in the Sea of Azov coincided with the period of increase in both global and regional temperatures, but the causes for these processes may be different.

Since the relationship between salinity and freshwater balance during the desalination period is low, it is possible that during this period the effect of water exchange with the Black Sea was enhanced. This cannot be verified within the framework of the proposed model due to the functional dependence of water exchange according to formulas (4).

Conclusions

After an extreme increase in the annual average salinity mean for the Sea of Azov up to 13.8‰ in 1976, it began to decline until 2006 and reached a level of 9.5‰; then it began to increase again at a faster rate than during previous sea salinization periods in 1965–1976. In 2020, sea salinity exceeded 14‰ and is continuing to rise.

One of the main causes for the Sea of Azov salinization after 2007 is the lack of water in the Don (and partly in the Kuban basin), which has been going on for more than 15 years. However, this factor alone is not enough to explain both the salinity decrease in the last quarter of the 20th century and its rapid increase in 2007–2020.

Using a mathematical model of the Sea of Azov water and salt balance, where the basin was considered as a single water body, it was demonstrated for annual average values that evaporation plays an important role in both salinization periods, but in the first period the determining effect was exerted by wind speed, and in the second period – by temperature and humidity conditions.

Based on the foregoing, it can be assumed that the change from a low-water period to a high-water period in the Sea of Azov region may not be a sufficient cause for a significant decrease in water salinity under warming conditions.

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Lyudmila V. Dashkevich – development of the general vision of the study and the results analysis; data preparation for the study; analysis of variability of all the water balance components

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