Long-term and seasonal anomalies of the Sea of the Azov thermohaline structure for 1913 – 2018

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Abstract. Variability of temperature and salinity as well as quantifying global trends are fundamental for understanding changes in the Earth's climate. In current paper, a long-term variability of the hydrological regime of the Sea of Azov for 1913–2018 is studied. On the basis of oceanographic information, the seasonal variability of temperature and salinity by the areas of the Sea of Azov is analysed. Temperature anomalies have been revealed, periods of salinization and desalination of the Sea of Azov have been noted and linear trends of the anomaly have been obtained.

1. Introduction
The main problem of regional oceanology is to study changes in the hydrometeorological regime of the inland seas. Temperature anomalies monitoring is needed to understand ecosystems trends and changes [1]. Shallowness and limited water exchange with the World Ocean, as well as the developing industrial infrastructure increase the dependence of the thermohaline structure of the Sea of Azov waters on regional climatic changes and anthropogenic impact [2]. All these issues require the study of long-term fluctuations of the hydrometeorological regime of the Sea of Azov and the determination of its trends in the modern period. This paper investigates the long-term variability of the hydrological regime of the Sea of Azov based on in situ data observation for the years of 1913–2018.

2. Research area
Research is carried out in one of the most continental seas – the Sea of Azov, which occupies an intermediate position between sea and freshwater bodies [3]. The presence of river waters inflow, which makes up to 12% of the volume of seawater, and a difficult water exchange with the Black Sea, determine its low salinity. The basin of the Sea of Azov, heterogeneous in depth, was divided into three areas: I – Taganrog Bay; II – Sea of Azov; III – Kerch Strait and adjacent parts of the Azov and Black Seas (Figure 1). The division was made for a more accurate assessment in the shallow water part (~14 m) and in the deep water part (~200 m).

3. Materials and methods
3.1. Oceanographic database
In current research we used in situ observation data of temperature and salinity of the Sea of Azov, obtained from the SSC RAS oceanographic database [4], supplemented by data from the open resource a http://atlas.ssc-ras.ru/azs/azs-invent.html [5], as well as data from the oceanographic data...
bank of the Marine Hydrophysical Institute RAS [6]. The generalized database processing is done using the Python software package. (66609 stations).

Figure 1. Image of the investigated area on the map. Blue rectangles indicate the boundaries of areas:
I – Taganrog Bay: 46°60’–47°30’ N, 37°75’–39°30’ E;
II – Sea of Azov;
III – Kerch Strait and adjacent parts of the Azov and Black Seas: 35°50’–37°70’ N, 45°–45°45’ E.

3.2. Estimation of anomalies
Monthly averages of temperature and salinity were calculated as normalized anomalies $A_i = (T_i - T_\text{в})/\sigma$, where $T_i$ is the monthly temperature average, $T_\text{в}$ is the average of water temperature for the calculated month for 1913–2018, $\sigma$ is the standard deviation of monthly averages for the same period [7]. Further, the anomaly coefficients classification will be used: less than 0.5 – insignificant, 0.5–1 – weak, 1–1.5 – moderate, 1.5–2 – strong, more than 2 – very strong.

4. Results and discussion

4.1. Features of temperature anomalies in the Sea of Azov areas
Data analysis has revealed long-term climate fluctuations. In areas I and III, it is difficult to identify seasonal and interannual cycles of anomalies. (Figure 2).

Figure 2. Heat maps of temperature anomalies by the areas of the Sea of Azov.

However, in Area I for the period of 2000–2018, positive anomalies prevail in the spring-summer period. Area II contains the greatest amount of water temperatures. In 1947–1957 and 1994–2018, seasonal changes in anomalies can be traced. Negative anomalies in the autumn-winter period are
replaced by positive anomalies in the spring-summer period. The opposite trend was observed in 1960–1977 and 1984–1990. During these periods, positive anomalies in the autumn-winter period were replaced by negative anomalies in the spring-summer period.

Temperature anomaly diagrams for the Sea of Azov areas are based on the classification of anomalies (Figure 3). In Area I, negative annual average anomalies prevailed in 1947–1961, and strong anomalies were recorded in 1958 and 1961; in 1969–1980 negative anomalies prevailed, except for 0.89 in 1972; the period of weak negative anomalies prevailed in 1986–2002, except for a strong positive anomaly of 1.2 in 1998 and weak one of 0.51 in 1999; further in 2003–2018 insignificant and weak positive anomalies dominated. In Area II, in 1922–1935, weak positive anomalies were recorded, these were replaced by a short period of negative anomalies in 1937–1939; 1946–1960 began with a strong positive anomaly of 1.58, and then weak negative anomalies prevailed; 1968–1994 was the period of minor negative anomalies, except for a moderate −1.21 anomaly in 1983 and a strong −1.81 anomaly in 1991; and then, until 2018, weak positive anomalies completely dominated. In Area III, the period of 1922–1935 began with weak positive anomalies (1923, 1924) followed by predominance of negative ones; in 1937–1939 moderate positive anomalies were recorded; 1947–1960 were characterized by predominance of negative anomalies; 1961–1966 was the period of weak positive anomalies; 1984–2002 was the period of minor anomalies, with manifestations of positive moderate in 1984, 1989 and 2002 and strong in 1999; a short period of weak anomalies was in 2003–2006.

Figure 3. Column diagrams of annual average temperature anomalies by the areas of the Sea of Azov

Time series of annual average and seasonal temperature anomalies for the entire observation period of 1913–2018 with distinguished periods of 1922–1946, 1947–1980 and 1985–2018 are shown in Figures 4, 5.

Figure 4. Annual average anomalies temperature in 1913–2018.
Positive trends are marked with red lines, negative trends are marked with blue, 5-year moving averages are shown in black. For the entire observation period of 1913–2018, there is a weak upward trend in temperature anomalies. Summer and autumn seasonal trends are similar to the general trend of annual average anomalies. Autumn and summer are characterized by the presence of downtrends in 1947–1980. In the winter season a downturn in the modern period was recorded.

4.2. Features of salinity anomalies in the Sea of Azov areas
The Sea of Azov is characterized by periods of salinization and desalination [8]. From figure 6 it may be seen that for each of the areas interannual periods of desalination (1922–1940, 1993–2010) and salinization (1955-1973, 2010–2018) may be clearly distinguished.

Figure 5. Temperatures of seasonal annual average anomalies in 1913–2018.

Figure 6. Heat maps of salinity anomalies by areas of the Sea of Azov.
A similar pattern can be traced when analyzing the diagrams of salinity anomalies shown in Figure 7. In Area I, short periods of salinization were recorded in 1947–1954 and 1968–1979; and 1996–2012 was a period of desalination. In Area II, periods of desalination (1922–1935, 1947–1958, 1977–1989, 1992–2012) and salinization (1937–1939, 1959–1976, 2013–2018) are clearly seen. In Area III a period of desalination was recorded in 1922–1939 with the presence of strong (−1.9 and −1.7) negative anomalies; 1960–1981 was the period of strong salinization of the Sea of Azov; 1987–1999 was the desalination period, replaced by a very strong positive abnormal salinity in 2000 (3.72), after which the salinization period continued until 2018.

Time series of annual average and seasonal salinity anomalies for the entire observation period of 1913–2018 and particular periods of 1922–1946, 1947–1980 and 1985–2018 are shown in Figure 8, 9. For the entire observation period of 1913–2018, there is downward trend in salinity anomalies. In the time periods of 1922–1946 and 1947–1980, there are upward trends and a sharp negative trend in the modern period of 1985–2018. In the winter season, the upward salinity trends for all considered periods have the greatest slope. The spring season stands out, since there is a weak downtrend in the period of 1922–1946.

![Figure 7](image1.png)

**Figure 7.** Column diagrams of annual average salinity anomalies by areas of the Sea of Azov.

Note that the coefficient of the general downtrend for 1913–2018 (-0.0065) is an order of magnitude less than the coefficient of the downtrend of the modern observation period of 1985–2018 (-0.0382). This trend contributes to the long-term tendency of changes in salinity anomalies, since upward salinity trends were recorded in previous periods.

![Figure 8](image2.png)

**Figure 8.** Annual average anomalies salinity in 1913–2018.
Figure 9. Seasonal annual average anomalies salinity in 1913–2018.

Conclusions
Analysis of the long-term variability of the hydrological regime of the Sea of Azov based on in situ observations for the period of 1913–2018 has shown the presence of upward trends in temperature anomalies and downward trends in salinity anomalies. The salinity of the Sea of Azov is characterized by periods of salinization in 1922–1946, 1947–1980 and desalination in 1985–2018, in the presence of weak salinization since 2010. It has been found that in most of the sea area in the periods of 1947–1957 and 1994–2018 negative anomalies in the autumn-winter period are replaced by positive anomalies in the spring-summer period, and the opposite trend was observed in 1960–1977 and 1984–1990. In the modern period, the trends of seasonal temperature anomalies are upward, except of winter. Thus, it may concluded that the global warming trends are confirmed by an increase in the annual average of the temperature of the Sea of Azov.

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