THERMAL REGIME OF THE NORTHWESTERN PART OF THE BLACK SEA

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ABSTRACT:

The spatio-temporal features of the surface water thermal regime of the northwestern part of the Black Sea, its bays and estuaries have been studied. Based on the long-term observations, the increase in the air and water temperatures was identified. Since 1894 the mean annual air temperature in Odesa city has increased by at least 2.5 °C. Also significant, but somewhat smaller (about 2.0 °C), is the increase in the water temperature. The July and August water temperature has the biggest increase. Water temperatures generally are higher than the air temperature, but this ratio is varying in value and sign for different seasons. In January–February, when it is the coldest, the water temperature is higher than the air temperature. In spring and summer, the air heats up faster than the water and it is warmer than water. In autumn and December, the sea water temperature usually is significantly higher than the air temperature. In spring and summer, the water temperatures in the bays and estuaries are higher than the water temperatures in the sea. In autumn and winter, it is the other way around. The dominance of the northwest and the north winds in the studied region is often induces the noticeable decrease in the water temperature near the coast. It was shown that even light winds have the impact on the spatial distribution of sea water temperature.

Key-words: *Air temperature, Water temperature, Black Sea, Wind; Remote Sensing.*

1. INTRODUCTION

The Black Sea is a unique sea, eighty-seven percent of which is fulfilled the hydrogen sulfide. The most environmentally sensitive area of the Black Sea for climate change and anthropogenic influence is northwestern part of the Black Sea shelf. This was indicated with assessment data of the ecosystem of the Black Sea to MSFD descriptors (Directive 2008/56 / EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) presented in (Slobodnik, et al. 2020a, 2020b, 2020c). As it was shown in study (Komorin, 2021) the water temperature is the one of the main indicators of marine water state that influence to the sustainability of the marine shelf ecosystem. There are quite a few papers devoted to the thermal regime of the Black Sea. In particular, the study (Ilyin, et al., 2012) shows that within the coastal zone the mean annual water temperature is significantly higher than the air temperature. This excess in the northwestern part of the Black Sea is about 1 °C, which is less than near the coast of the Caucasus, where this excess is about 2 °C. This is due to the Main Black Sea Current, in which water moves counter-clockwise. Therefore, the relatively low water temperature near the northwestern shores is due to the movement of the sea water from the north to the south.

The study (Ilyin, et al., 2012) contains information on the mean long-term water temperature at several observation points located on the sea shore. Thus, the mean annual water temperatures for

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the period 1915–2011 (Odesa Port) were 11.1 °C, and 12.1 °C (period of 1951–2011, in the village Prymorske). The long-term mean water temperatures for August (the warmest month for both points) are 20.7 °C and 22.5 °C accordingly. The above-mentioned study showed the existence of noticeable increase of water temperature in the Black Sea, with the average rate of 0.08 °C per decade during period 1923–2011. Considerable research of the water temperature in the northwestern part of the Black Sea was carried out in the study (Popov, et al., 2016), where images and maps of the characteristic temperatures of the sea water surface layer for each month of year were presented. According to those data, the lowest water temperature usually observed in February and the highest – in August. The studies (Ilyin, et al., 2012; Bolshakov, Matygin, 2017) highlighted unusually high and low water temperatures in Odesa. Thus, on July 17, 1976, the water temperature there was only 7.2 °C, and on August 13, 1983 it was only 8.0 °C. The very high water temperature (31.2 °C) was recorded on August 11, 2010.

There are many publications (Adrian, et al., 2009; Czernecki, Ptak, 2018; Lieberherr, Wunderle, 2018; Ptak, et al., 2020; Shaltout, Omstedt, 2014; Vyshnevskyi, Shevchuk, 2021; Woolway, et al., 2017) where the facts of the increase in the water temperature had been detected.

It should be noted, that the observation at coastal zone does not represent the spatio-temporal patterns for the whole region of the open sea water temperature. This is difficult to carry out even with the use of the research fleet data. The issue could be resolved with the using of remote sensing, in particular the using of data from the thermal bands of Landsat 8 and Landsat 9 satellites. However, until recently, such data for the studied region of the Black Sea were very limited, mainly due to the small number of the good quality (without clouds) satellite images. According to the authors, the appearance of a sufficiently large number of them makes it possible to study not only seasonal features of surface water temperature, but also features caused by even a light wind.

Therefore, the main purpose of this research is the identification of the spatio-temporal patterns in the recent distribution of the north-western region of the Black Sea water temperature and its long-term trends.

2. STUDY AREA

The studied area of the Black Sea, as the title of the article implies, is located in its northwestern part (**Fig. 1**). Observations of the climate and water temperature are carried out at the number of meteorological and hydrological stations. The majority of the analyzed information are based on the observations at Odesa and Vylkove meteorological stations, which are located, respectively, in the northern and southern parts of the studied region.

Fig. 1. Location of the studied part of the Black Sea and hydrometeorological observation points: 1 – Black Sea, 2 – lake Sasyk, 3 – Tuzliv estuaries, 4 – Dniester estuary, 5–6 – Odesa and Vylkove meteorological stations, 7–8 – Odesa and Prymorske hydrological stations.

Odesa meteorological station is located near the center of the city only 150 m from the sea. The observations started there in 1894, and since then the meteorological station was never moved. Vylkove meteorological station is located on the bank of the Danube River, 13 km from the sea (**Fig. 1**).

3. DATA AND METHODS

The study of air temperature and its long-term changes for Odesa meteorological station was carried out for the period 1894–2021, and for Vylkove meteorological station for the period of 1961–2021. The water temperature in Odesa is measured near the city centre in the port, where the depth is quite significant. At the same time, at Prymorske station, the water temperature is measured on the sea beach, where the depth is small. As will be shown below, this has some effect on the results, primarily on the intra-annual temperature distribution.

Changes in the mean annual water temperature at Odesa meteorological station were identified for the period of 1915–2021, and the mean monthly water temperature for the period of 1961–2021. Data on water temperature at Prymorske station were analysed for the period of 2016–2021.

In addition to the data from the regular monitoring, in our research were used the remote sensing data. The main attention was paid to the images from Landsat 8 and Landsat 9 satellites, which are available on the website https://earthexplorer.usgs.gov. The images of series LC08_L1TP_180028 and LC09_L1TP_180028 cover most of the studied region. The time of the earth surveying of the studied area is 08:44 GMT, which is corresponds to about the noon of the local time. The spatial resolution of B10 thermal band of these satellite images is 100 m, the revisit time is 16 days.

Although Landsat 8 satellite has been in the orbit since 2013, there are not many high-quality images, especially in the cold season. The largest part of images is completely or partially overcast. There are even fewer high-quality images from Landsat 9 satellite, which was launched in September 2021. In research we had used images that are not overcast and those are representative for the different seasons. Satellite images were processed using ArcMap 10 program.

Water surface temperature was calculated applying formulas recommended by NASA:

for Landsat 8:

t = (1321.08/(Ln((774.89/(("LC8_B10.TIF" * 0.0003342)+0.1))+1)))-273.15,

for Landsat 9 satellite:

t = (1329.2405/(Ln((799.0284/(("LC9_L1TP_B10.TIF" * 0.00038)+0.1))+1)))-273.15.

The reliability of these regressions was confirmed by many studies (Schaeffer et al, 2018; Vyshnevskyi, Shevchuk, 2018).

The territory, which does not belong to water area, was identified using the calculation of Normalized Difference Pond Index (NDPI). This index is calculated by the equation

NDPI = (B6 – B3) / (B6 + B3),

in which B3 and B6 are the meanings of corresponded values of the satellites Landsat bands. The territory, which is not the water area, was presented in grey color for better visualization. The territory that did not get into the pictures is shown in white.

4. RESULTS AND DISCUSSIONS

4.1. Air temperature and its long-term changes

The considerable duration of observations at Odesa and Vylkove meteorological stations makes it possible to characterize the air temperature in the studied region and its long-term changes. As in many regions of the world, the air temperature here has risen significantly. During the period 1894–2021, the air temperature in Odesa increased by more than 2.5 °C, the most in the last 30 years.

At the same time, in case of approximation by a linear trend, this increase would be noticeably less – about 1.8 °C. The changes of air temperature during 1894–2021 according to the linear trend are 0.15 °C per decade (**Fig. 2**).

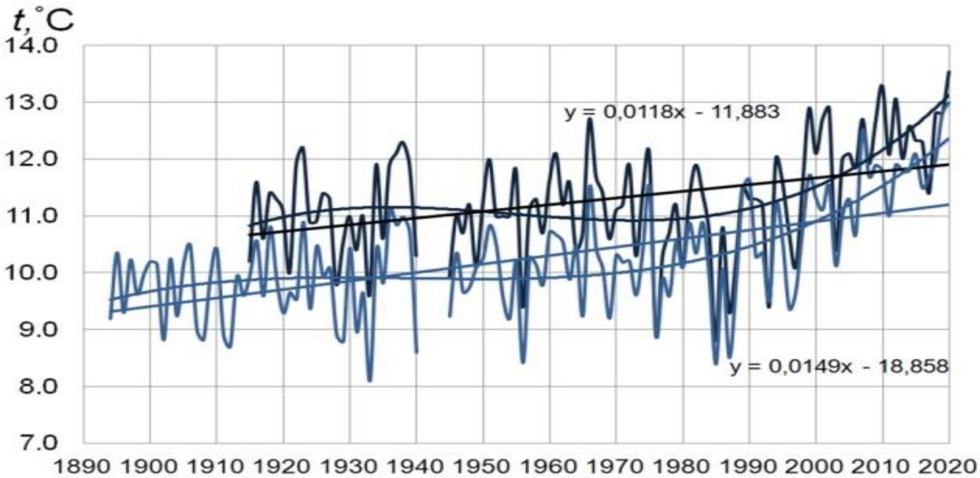


Fig. 2. Long-term changes in the average annual of air (light blue) and water temperature (deep blue) in Odesa.

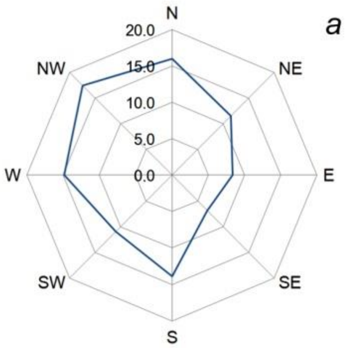
Data processing for the 30-years period 1961–1990 shows the mean annual air temperature in Odesa is 10.2 °C and the corresponding value for the period 1991–2020 is 11.3 °C. The air temperature in Vylkovo during these periods is 11.1 °C and 12.2 °C respectively. As it can be seen in both cases, the difference in air temperature is 1.1 °C. The year 2020 turned out to be the warmest in the entire history of the observations, when the mean annual air temperature in Odesa reached 13.0 °C, and in Vylkove – 13.6 °C.

During the last 30 years, the highest mean air temperature in Odesa (23.4 °C) is observed in July, and the lowest (minus 0.4 °C) in February. The highest air temperature in Vylkovo is also observed in July (24.1 °C), the lowest one – in January (plus 0.4 °C). Compared to the previous 30-year period (1961–1990), the air temperature increased in all months of the year, but the most in July–August.

4.2. Wind regime

To some extent, the water temperature in the northwestern part of the Black Sea depends on the speed and direction of the wind. It is well known that wind can cause the changes in water level, which are accompanied by significant changes in temperatures. The cases of the low water temperatures in Odesa which were mentioned in the Introduction were caused by the northwest wind. In general, the northwest and the north winds dominate in the studied part of the Black Sea. The predominant wind directions in Odesa are from the northwest, which occurs in 17.5 % of the observations. Such recurrence for the July–August period increases to 22–23 %. The prevailing wind in Vylkovo is from the north. The south wind at this station has somewhat lower recurrence (**Fig. 3**).

According to the available data the wind speed in the studied region is low. Its mean long-term value at Odesa station is 2.9 m/sec. The highest wind speed is observed in November–December (3.4–3.5 m/sec), the lowest one – in July–August (2.3 m/sec). According to the chronological observations, there is the decreasing trend of wind speed.



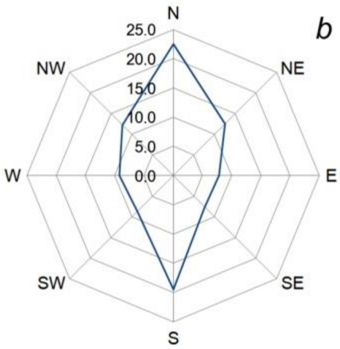


Fig. 3. Mean annual recurrence of wind at Odesa (*a*) and Vylkove (*b*) meteorological stations during 1991–2020.

4.3. Water temperature and its long-term changes

A comparison of the air and water temperature data (see **Fig. 2**) shows that the water temperature is generally higher than the air temperature. This excess is explained by the fact that the main absorption of the Sun's energy occurs in the upper layer of water, where, in fact, the temperature is measured. In addition, the fact that seawater has a certain minimum temperature, while the air temperature does not have such limit, must be considered. For the northwestern part of the Black Sea, which has a salinity approximately half that of the World Ocean, this minimum is about minus 1 °C.

During the observation period 1915–2021, the mean annual water temperature in the studied part of the Black Sea increased significantly – by approximately 2.0 °C. According to the linear trend, the increase is less – about 1.1 °C (see **Fig. 2**). However, this increase is still greater than that obtained in the study (Ilyin, et al, 2012) for the period 1923–2011.

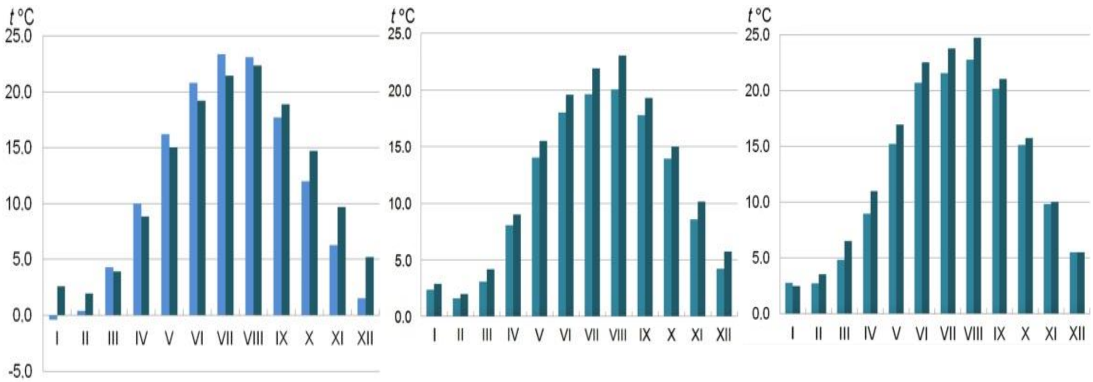
In 1991–2021, the mean annual water temperature in Odesa was 12.0 °C, in 2001–2021 – 12.4 °C. In 2020, which turned out to be the warmest, the average annual water temperature in Odesa reached 13.4 °C.

Analysis of **Fig. 2** shows that mean annual water temperature generally increases more slowly than the air temperature. This can be explained by the large volume of water in the Black Sea and the inertia of its heating. The difference between the mean annual air and water temperature in the middle of the 20th century was about 1.1 °C, nowadays it is 0.7–0.8 °C. A somewhat greater increase in air temperature compared to water temperature was recorded for the Kakhovske reservoir located **r**elatively not far from the Black Sea (Vyshnevskyi, Shevchuk, 2021). However, when the volume of water is small, the increase in air and water temperature is practically similar.

During the year, the ratio between air and water temperature does not remain constant. In January–February, when it is the coldest, the water temperature is higher than the air temperature. In spring and summer, the air temperature is higher than the water temperature. In autumn and December, the water temperature becomes significantly higher than the air temperature (**Fig. 4a**).

Different rates (and signs) of the differences in the values of monthly averaged air and water temperatures causes, that the correlation between these parameters varies throughout the year. However, the correlation between the air and water temperatures is generally strong. For the mean annual values in Odesa and period 1961–2020, the correlation coefficient is r = 0.893, for the mean values of the period of May to October relevant value of r = 0.864, for the mean values of summer period – r = 0.856.

Comparison of the monthly means of water temperatures averaged for the two 30 years periods (1961–1990) and (1991–2020) clearly displays the increase in water temperature, throughout a year, with little bigger increases in July and August (**Fig. 4b**).



(a) (b) (c)

Fig. 4. Year course of temperature: a – monthly means of temperature air (left columns) and water (right columns) in Odesa averaged for the period of 1991–2020; b – water temperature by months in Odesa: left columns – 1961–1990, right columns – 1991–2020; c – water temperature by months in 2016–2021: left columns – in Odesa, right columns – in Prymorske.

Comparison of the averaged values of water temperatures monthly means in Prymorske and in Odesa detected the differences in these values. In spring and summer, the shallow Zhebryanivska Bay, in which Prymorske station is located, warms up faster and as result the water at this station is higher than in Odesa port. In January, the water temperature in this bay is lower than in Odesa (**Fig. 4c**). As can be seen in **Fig. 4c**, in recent years the water temperature in August at Prymorske station approached the mark of 25 °C (the values typical for resorts in Bulgaria).

There is a close correlation (r = 0.989) between the data on mean annual water temperature in Odesa and Prymorske, which has the form

$$t_{\text{Primor}} = 1.0598 * t_{\text{Odesa}} + 0.396\ (°C).$$

According to this regression, the mean water temperature at Prymorske station in 1991–2021 is 13.1 °C, which is higher than in Odesa by 1.1 °C. This is close to the difference in air temperature.

4.4. Spatial features of the water temperature

The given data sufficiently fully represents the temporal patterns of water temperature at Odesa and Prymorske stations. However, the spatial patterns of the water temperature remain unclear, primarily in the open sea and estuaries. These gaps can be filled with the use of remote sensing, namely with data from thermal bands of Landsat 8 and Landsat 9 satellites.

Corresponding data shows that at the beginning of the year the water temperature in the Black Sea is low, especially in the bays and estuaries. It is the highest in the open part of the sea, where there is greater depth, heat reserves and better mixing. At this time shallow bays of the sea can be covered with ice (**Fig. 5a**). Similar conditions are observed in February and early spring, with the difference that in March the shallow bays of the sea already begin to warm up (**Fig. 5b**).

A comparison of images obtained in January and March shows that the sea water temperature may be even lower in the latter case. First of all, it depends on the air temperature observed in a certain month or season. Thus, the weather in January and February 2014 in the studied region was cool. On the other hand, the weather in December 2021 was warmer than normal and this affected the water temperature not only this but also the next month. In general, according to the long-term observations, the water temperature in March is a little bit higher than in January (see **Fig. 4b**).

Meanwhile, the water temperature is affected by specific weather conditions. This, in particular, applies to the conditions of 11.03.2014. Since the night before a rather strong north wind was observed in the studied region. At Odesa and Vylkove meteorological stations, its speed was 6–8 m/sec. This wind caused the decrease of water temperature near the shore.

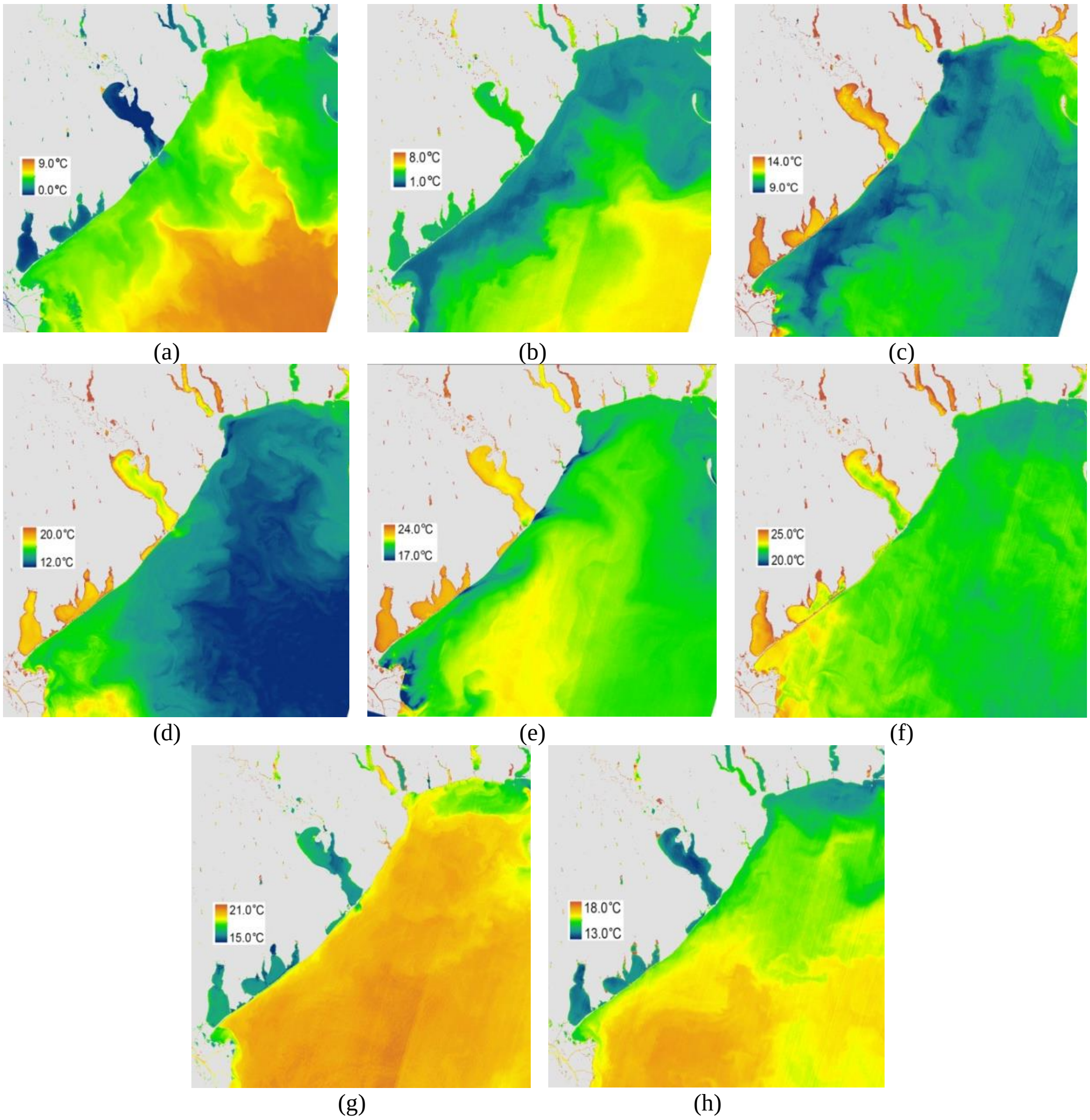


Fig. 5. Spatial features of water temperature in the northwestern part of the Black Sea according to data from Landsat 8 and Landsat 9 satellites: a) on January 4, 2022; b) on March 11, 2014; c) on April 28, 2020; d) on May 12, 2022; e) on July 20, 2015; f) on August 18, 2020; g) on September 19, 2014; h) on October 16, 2018.

It can be added that on March 11, 2014, the mean daily air temperature in Odesa was 7.9 °C, in Vylkove – 6.4 °C. In turn, the mean daily water temperature that day in Odesa was 4.0 °C, in Prymorske – 3.2 °C. As can be seen from these data and those ones which are shown on **Fig. 4b**, there is a close relationship between the temperature measured and identified with use of the satellite image.

In April, when it warms up noticeably, the highest temperature is observed in shallow bays and water bodies isolated from the sea. This, in particular, is typical for the lake Sasyk, Dniester estuary and other water bodies (**Fig. 5c**).

Analysis of **Fig. 5c** allows us to assume that on April 28, 2020, a wind from the south or southwest was probably observed. This, in particular, is evidenced by the appearance of cool water in the southern part of the Dniester estuary, as well as the relatively high temperature in its northern and northeastern parts. Indeed, in the first half of this day, up to the time of the satellite survey, a south wind with a speed of 3–4 m/sec was observed at the Odesa meteorological station. At Vylkove station, the wind was of approximately the same strength from the south and southwest. On April 28, 2020, the mean daily air temperature in Odesa was 11.7 °C, in Vylkove it was 13.4 °C. The water temperature in Odesa was 9.4 °C, in Prymorske – 13.2 °C. The latest data show that water temperature at Prymorske station in spring can be significantly higher than the water temperature at Odesa station, which is located further north and has a greater depth. We should add that at the end of April there is usually a peak of spring flood of the Danube River. The consequence of this is a slight increase in water temperature near its mouth, because the water masses of the Danube River warm up faster than that of the Black Sea.

In comparison to the April values, the May air and water temperatures rise significantly. First of all, this applies to shallow water bodies, which warm up faster than the Black Sea. At this time, the water temperature in shallow water bodies can rise to 17–18 °C. Simultaneously the sea remains significantly colder. The characteristic conditions, which confirms these features, were observed on May 12, 2022 (**Fig. 5d**). In the first half of this day a south wind with a speed of 3–4 m/sec was recorded in the studied region. The mean daily air temperature at Odesa station was 16.8 °C.

Analysis of **Fig. 5d** shows that in May (this also applies to June and July) the spatial difference in water temperature can be very significant. This can be explained by the slow heating of the Black Sea water mass. In case of strong wind, the water temperature near the shore can sharply drop or rise by several degrees.

The condition recorded on the satellite image from July 20, 2015 seems interesting. This image shows the existence of several zones with a low water temperature near the shore (**Fig. 5e**). At the beginning of this day a south wind with a speed of 2–3 m/sec was observed in the studied region. At noon, the wind in Odesa was from the south-southeast, its speed increased to 5 m/sec. A similar wind was observed in Vylkovo, but in the afternoon its direction was from the south. The mean daily air temperature in Odesa on July 20, 2015 was 23.0 °C, in Vylkove – 23.6 °C. The water temperature in Odesa was 19.0 °C. As it could be seen on the image **Fig. 5e**, the even gentle south wind can cause the appearance of the relatively small upwelling zones at some parts of the coast, where the temperature is lower than in the surrounding area.

In August, when the water temperature in the sea is usually the highest, the difference between the water temperatures in the open sea and the bay's water temperatures somewhat decreases. This feature confirms the conditions observed on August 18, 2020 (**Fig. 5f**). At the beginning of this day a light wind of a variable direction was observed both at the Odesa and Vylkove meteorological stations. Later on in the day, from 6:00 a.m. to 12:00 p.m., the wind prevailing direction became the south-southeast, with a speed of 3–4 m/sec. The mean daily air temperature at Odesa meteorological station was 23.1 °C, at Vylkove meteorological station – 22.7 °C. The mean daily water temperature was as follows: Odesa – 21.9 °C, Prymorske – 25.1 °C. Similarly, to other cases, the comparison of measured water temperature and values, determined from the satellite image, shows a good correlation.

The decrease in the air temperature, which is usually observed in the second half of September, causes the fact that the water temperature in the sea becomes warmer than near the shore – primarily in its open part, which is deeper and located further south. This can be seen on the example observed on September 19, 2014 (**Fig. 5g**). In the first half of this day the light wind with a speed of 2–3 m/sec from the north-northeast was observed in the studied region. The mean daily air temperature in Odesa was 17.7 °C, in Vylkove – 16.1 °C. The water temperature was as follows: Odesa – 20.3 °C, Prymorske – 18.8 °C.

As the weather gets colder (October), the open deep waters of the studied region of the Black Sea cools down slower than its shallow waters. These conditions can be seen on the example conditions, observed on October 16, 2018 (**Fig. 5h**).

In the first half of the day on October 16, 2018, a light northeast wind was observed in the studied region. Its speed at Odesa and Vylkove meteorological stations was 2–3 m/sec. The mean daily air temperature in Odesa was 16.0 °C, in Vylkove – 14.7 °C. The water temperature was as follows: Odesa – 15.6 °C, Prymorske – 15.5 °C.

The given data make it possible to characterize the main spatio-temporal features of the water temperature in the northwestern part of the Black Sea. Observation data, as well as data from remote sensing, show that the lowest water temperature in the open part of the sea is observed in the second half of winter. With the onset of spring, the shallow bays of the sea begin to warm up, and therefore the water temperature here becomes higher than in open sea. It is important that spatial differences in water temperature in the first half of the year are very significant – up to 8–10 °C. Relatively higher water temperature in the bays of the sea is observed until the end of summer. In September, when the air temperature drops, water temperature there becomes lower than in the open sea. The subsequent decrease in air temperature is usually accompanied by a drop in water temperature in shallow bays and some slower cooling in the deep open part of the sea.

It could be added that water has a great capacity to hold energy. It takes a lot of energy to raise the temperature, but once the water temperature is raised, the heat energy is dissipating very slowly.

Even the light wind has a significant influence on the spatial sea water temperature distribution. The dominance of the northwest and the north winds in the studied part of the Black Sea often leads to a noticeable decrease in water temperature near the shore.

5. CONCLUSIONS

During the long-term observation period, the air and water temperature in the northwestern part of the Black Sea has increased significantly. Since 1894, the mean annual air temperature in Odesa has risen by at least 2.5 °C. Significant, but somewhat smaller (about 2 °C), is the increase in water temperature. During 1991–2021, the mean annual water temperature in Odesa was 12.0 °C, in Prymorske, which lies to the south near the mouth of the Danube River, is 13.1 °C. The highest annual water temperature during entire observation period was observed in 2020: in Odesa it was 13.5 °C, in Prymorske – 13.4 °C.

The water temperature rose the most in July and August. During 1991–2021, the water temperature in Odesa in these months averaged 21.5 °C and 22.4 °C, and in recent years (2016–2021) – 21.8 °C and 22.7 °C, respectively. The water temperature in Prymorske (2016–2021) in these months is even higher – 23.9 °C and 24.7 °C.

The mean annual water temperature is generally higher than the air temperature, but in individual seasons this ratio is different. In January–February, when it is the coldest, the water temperature is higher than the air temperature. In spring and summer, the air temperature is higher than the water temperature. In autumn and in December, the water temperature is significantly higher than the air temperature.

In spring and summer, the water temperature in the bays is higher than the sea temperature, in autumn and winter, the opposite is true.

Quite often, the water temperature is affected by the wind. The predominance of the northwest and the north winds in the studied region is often accompanied by a noticeable decrease in water temperature near the coast. The reliable satellite images show that even the light wind has the impact on the spatial distribution of sea water temperature.

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