Original paper

Sea Surface Temperature Variability off the Crimea Coast in 2022–2023 According to *in situ* and Satellite Measurements

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Abstract
The paper studies the variability of the temperature field at the sea surface on different time scales using hydrological measurements made off the coast of Crimea during 2022–2023 cruises of R/V *Professor Vodyanitsky* and *Copernicus* satellite data. It is shown that the intra-annual temperature amplitude according to *in situ* measurements in 2022 was 18.2 °C, whereas in 2023, it was 16.6 °C. The maximum ranges of spatial temperature changes at the polygon (up to 4–5 °C) were observed during periods of intense heating and cooling of surface waters in April–May and December 2022 and October 2023. On the synoptic scale, the periods of temperature increases (decreases) corresponded to those of local wind decreases (increases) with a delay in the temperature response to changes in the wind speed by 10–12 hours. Satellite data showed differences in the temperature intra-annual cycle and the level of its synoptic variability in 2022 and 2023 from climate norms. In 2022, the minimum and maximum temperatures in the intra-annual cycle were observed two weeks later than according to climate data. In 2023, the time of occurrence of the minimum corresponded to the climate one, and the maximum was observed two weeks earlier than it had been expected from the climate data. The main maximum in the level of synoptic temperature variability was observed in November 2022 and in December 2023, but not in May as it had been expected from the climate data. It is shown that from 2022 to 2023, predominantly positive average monthly temperature anomalies against the climate norms were observed. This reflects the upward tendency in temperature over the past two years.

Keywords: Black Sea, sea surface temperature, satellite measurements, *in situ* measurements, spatiotemporal variability

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Изменчивость температуры поверхности моря у берегов Крыма в 2022–2023 годах по данным экспедиционных и спутниковых измерений

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Аннотация
По данным гидрологических измерений, выполненных у берегов Крыма в ходе рейсов НИС «Профессор Водяницкий» в 2022–2023 гг., и спутниковым данным *Copernicus* исследована изменчивость поля температуры на поверхности моря на разных временны́х масштабах. По данным контактных измерений показано, что внутригодовая амплитуда температуры в 2022 г. составила 18.2 °C, в 2023 г. – 16.6 °C. Максимальные диапазоны пространственных изменений температуры на полигоне (до 4–5 °C) наблюдались в периоды интенсивного прогрева и охлаждения поверхностных вод в апреле – мае и декабре 2022 г. и в октябре 2023 г. На синоптическом масштабе периоды повышения (понижения) температуры соответствовали периодам ослабления (усиления) локального ветра с запаздыванием реакции температуры на изменения скорости ветра на 10–12 ч. По спутниковым данным показаны отличия внутригодового цикла температуры и уровня ее синоптической изменчивости в 2022 и 2023 гг. от климатических норм. В 2022 г. минимум и максимум температуры наблюдались на две недели позже, чем по климатическим данным, в 2023 г. время наступления минимума соответствовало климатическому, а максимум наблюдался на две недели раньше, чем по климатическим данным. Основной максимум уровня синоптической изменчивости температуры прослеживался в 2022 г. в ноябре, в 2023 г. – в декабре, а не в мае, как по климатическим данным. Показано, что в период с 2022 по 2023 г. наблюдались преимущественно положительные среднемесячные аномалии температуры относительно климатических норм, отражающие тенденцию к повышению температуры в течение последних двух лет.

Ключевые слова: Черное море, температура поверхности моря, спутниковые измерения, контактные измерения, пространственно-временная изменчивость

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Introduction

The solution of modern problems related to the rational use of the Black Sea resources and preservation of its ecosystem requires constant monitoring of the waters hydrological structure state. Particular emphasis is placed on the investigation of the temperature field variability, as this parameter represents a pivotal abiotic factor influencing the marine ecosystem. Works [1)] [1–7] show that seasonal and interannual variations are the main contributors to the total variability of the sea surface temperature (SST) field. It is shown that the SST seasonal variability is largely determined by the advection of waters by the Rim Current (RC) in addition to heating and cooling processes. Transport of warm waters with the RC from the east and southeast to the Crimean coast results in an increase in the SST in the winter–spring period, weakening of intra-annual temperature contrasts and, as a consequence, minimum level of the SST seasonal variability near the Crimean coast [6]. It is established that large-scale atmospheric processes and changes in the RC intensity influence the SST interannual variability [6, 8–10]. Works [3, 11–17] demonstrate that in recent years, a notable increase in the Black Sea temperature can be observed even in the cold intermediate layer.

Works [5, 7, 18–26] show that in addition to seasonal and interannual processes, the variability of the Black Sea temperature field is also influenced by a number of other factors including synoptic eddies, local meteorological conditions and upwelling. The intensive formation of synoptic meanders and circulations leading to the formation of temperature anomalies [24–26], as well as the export of the Azov Sea waters through the Kerch Strait [27], determined a high level of the SST synoptic variability within the coastal zone of Crimea from the Kerch Strait to the Heracleian Peninsula [7]. It is important to note that over the past decade, the hydrological water structure monitoring and assessment of the spatio-temporal evolution of the temperature field directly off the Crimean coast, where the anthropogenic impact is most pronounced, have been conducted primarily on the basis of *in situ* measurements on R/V *Professor Vodyanitsky* with a relatively large distance between stations (20–30 km). In this regard, the results of measurements made in 2022–2023 are of particular interest, given that hydrological surveys off the Crimean coast were conducted on a more frequent grid of stations and in a number of cruises the surveys were repeated twice. The repeat survey data obtained during the 122nd and 123rd cruises of R/V *Professor Vodyanitsky* in conjunction with satellite temperature measurements permitted a comprehensive analysis of the SST field spatial structure and characteristics of its synoptic variability off the Crimean coast during the summer of 2022 [30].

The objective of the present study is to examine the SST field variability in the northern Black Sea off the Crimean coast on different time scales. To this end, data collected during eight cruises of R/V *Professor Vodyanitsky* in 2022–2023 is integrated with *Copernicus* satellite data.

[1)] Nelepo, B.A., ed., 1984. [*Variability of Hydrophysical Fields of the Black Sea*]. Leningrad: Gidrometeoizdat, 240 p. (in Russian).

Materials and methods

In 2022 and 2023, hydrological measurements were carried out during the 121st, 122nd, 123rd, 124th, 125th, 126th, 127th and 129th cruises of R/V *Professor Vodyanitsky* off the Crimean coast within the Russian territorial waters (Fig. 1). Table shows timing of measurements and number of stations carried out during the cruises. In consequence of the diminished extent of the survey area in 2022–2023 in comparison with that of the preceding cruises, the number of hydrological stations within the polygon was augmented, thereby facilitating the acquisition of more comprehensive SST spatial distributions off the Crimean coast. The expedition time reserve made it possible to carry out repeated hydrological surveys in four cruises (122nd, 123rd, 127th and 129th), with the coordinates of the stations remaining almost identical throughout. Hydrological measurements were taken in all seasons in 2022 and in spring, summer and autumn in 2023, providing a comprehensive data set for the assessment of the SST seasonal changes. Seawater temperature was recorded at each station using IDRONAUT OCEAN SEVEN 320PlusM CTD measuring system with an error of 0.001 °C and a resolution of 0.0001 °C (http://www.technopolecom.ru/downloads/doc_212.pdf) predominantly during daylight hours. The temperature field distribution was analysed in the surface layer at a distance of 2 m. During all cruises, five multi-hour hydrological stations were carried out at locations indicated in Fig. 1.

In this study, we also used daily averaged data from the SST satellite measurements from 1 January 2008 to 31 December 2023 with an ultra-high spatial resolution of 0.01° × 0.01° from the Black Sea High Resolution and Ultra High Resolution

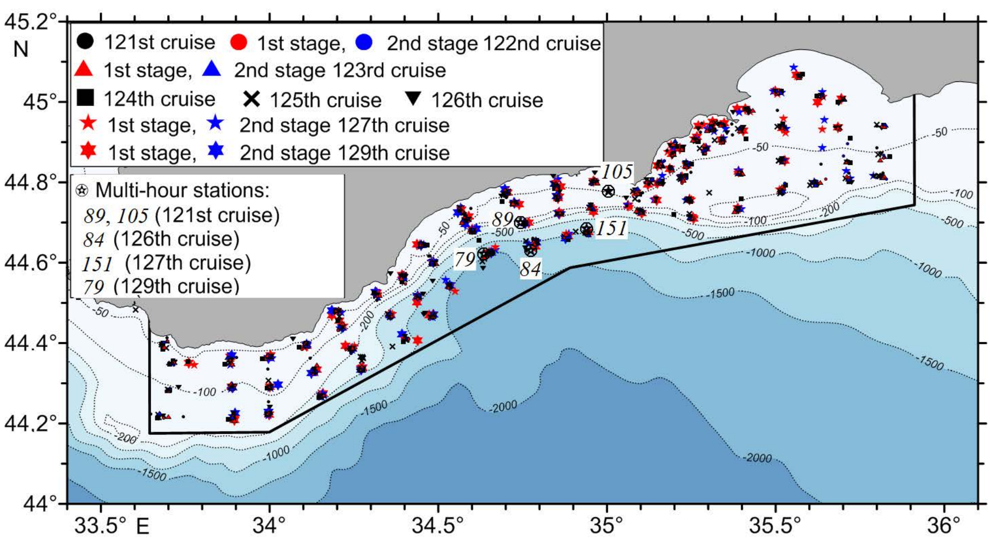

Fig. 1. Map of hydrological stations carried out off the Crimea coast during the 121st, 122nd, 123rd, 124th, 125th, 126th, 127th and 129th cruises of R/V *Professor Vodyanitsky*

Timing of measurements and number of stations carried out at the polygon during the cruises of R/V *Professor Vodyanitsky* in 2022–2023

Cruise number		Date	Number of stations
121		19.04.2022–14.05.2022	*87*
122	1st stage	07.06.2022–13.06.2022	*75*
	2nd stage	17.06.2022–23.06.2022	*73*
123	1st stage	16.08.2022–23.08.2022	*78*
	2nd stage	26.08.2022–31.08.2022	*78*
124		02.10.2022–22.10.2022	*113*
125		02.12.2022–25.12.2022	*128*
126		16.03.2023–07.04.2023	*90*
127	1st stage	14.06.2023–20.06.2023	*64*
	2nd stage	22.06.2023–05.07.2023	*71*
129	1st stage	05.10.2023–17.10.2023	*66*
	2nd stage	17.10.2023–25.10.2023	*34*

Sea Surface Temperature Analysis array [2)] (product SST_BS_SST_L4_NRT_OBSERVATIONS_010_006) of Copernicus Marine Environment Monitoring Service (CMEMS) obtained using advanced processing algorithms [31]. These data made it possible to calculate statistical characteristics of spatiotemporal temperature variability.

Actual wind speed values were selected from continuous records made at each station using the AIRMAR-220WX shipboard weather station and referred to the beginning of the hydrological sounding period.

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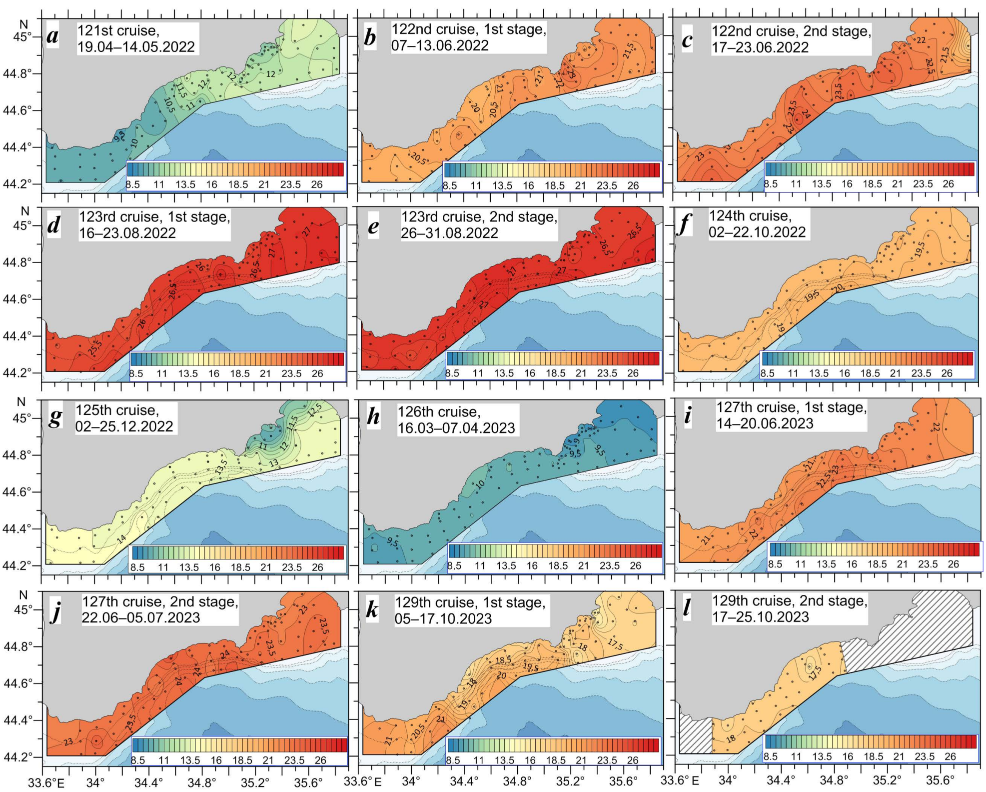
2) Black Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis / E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). https://doi.org/10.48670/moi-00159 (date of access: 25.11.2024).

Main results

The analysis of the *in situ* measurement data carried out in 2022–2023 revealed a complex pattern of the actual SST horizontal distributions (Fig. 2), which can be attributed to the combined influence of seasonal, synoptic and diurnal variability. It is important to note that the accurate accounting of the SST diurnal variations based on *in situ* data necessitates continuous measurement of data at each hydrological station for a minimum of one day. However, this is currently unfeasible within the constraints of the allocated time of cruises. Earlier estimates of the SST diurnal variations based on *in situ* and satellite data [32, 33] indicated that it could reach several degrees and was significantly influenced by the measurement area, season and local synoptic conditions (cloudiness and wind speed). The data obtained from the SST measurements at the multi-hour hydrological stations carried out during the 121st, 126th, 127th and 129th cruises also demonstrated that the SST diurnal variations exhibited notable differences on varying days, across different seasons and in multiple areas of the polygon, reaching a maximum of 1.6–2 °C. Conversely, during daylight hours, when the primary measurements were carried out at the polygon, the changes in the SST did not exceed 0.5 °C.



F i g . 2 . SST distribution according to the measurements carried out in the 121st (*a*), 122nd (*b*, *c*), 123rd (*d*, *e*), 124th (*f*), 125th (*g*), 126th (*h*), 127th (*i*, *j*) and 129th (*k*, *l*) cruises of R/V *Professor Vodyanitsky*

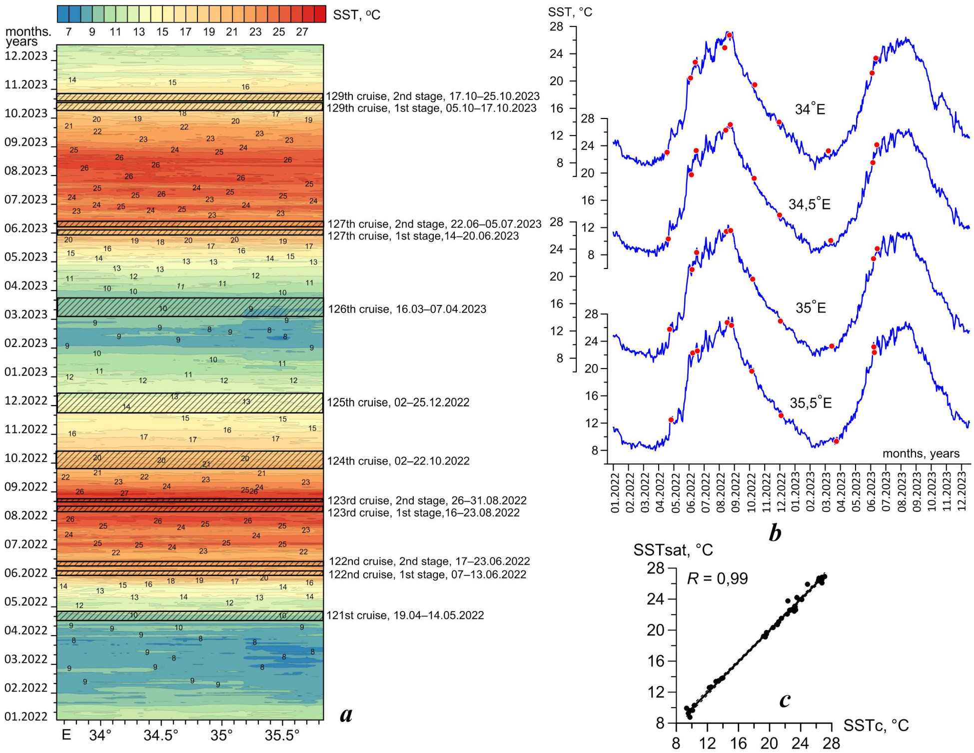
The SST spatial distributions from all surveys demonstrated that seasonal variability was most clearly evident in the SST fields. Thus, according to measurements taken in 2022, the SST minimum at the polygon was observed in April – May (121st cruise), with values fluctuating between 9.3 and 13.4 °C (Fig. 2, *a*). The SST values increased to 19.5–23.6 °C in the first half of June (122nd cruise, 1st stage) and to 17.5–24.5 °C at the end of June (122nd cruise, 2nd stage) (Fig. 2, *b*, *c*). During the second half of August, the maximum SST values were observed, reaching 24.9–27.5 and 25.6–27.5 °C, respectively, during both stages of the 123rd cruise (Fig. 2, *d*, *e*). In October (124th cruise), the SST decreased markedly, with values varying within the polygon from 18.7 to 20.3 °C (Fig. 2, *f*). In December (125th cruise), a further decrease in the SST values was observed, with a minimum range of 9.5–14.5 °C. (Fig. 2, *g*).

According to measurements taken in 2023, the lowest SST values (8.7–10.2 °C) were observed in the second half of March and early April (126th cruise) (Fig. 2, *h*). During the summer months, specifically the second half of June, there was a notable rise in the SST values, which reached a range of 20.5–23.5 °C during the 1st stage of the 127th cruise and increased subsequently to a range of 22.2–25.3 °C during the 2nd stage of the cruise (Fig. 2, *i*, *j*). In the autumn, in October, a decrease in the SST was observed, with values ranging from 15.5 to 21.5 °C during the 1st stage of the 129th cruise and from 16.1 to 18.4 °C during its 2nd stage (Fig. 2, *k*, *l*).

Thus, the minimum SST values were observed in spring 2022 (19 April – 14 May) and 2023 (16 March – 7 April), while the maximum ones were observed in late August 2022 and in late June – early July 2023. The intra-annual SST amplitude, as determined by measurements conducted in 2022, was 18.2 °C, while in 2023 it was 16.6 °C.

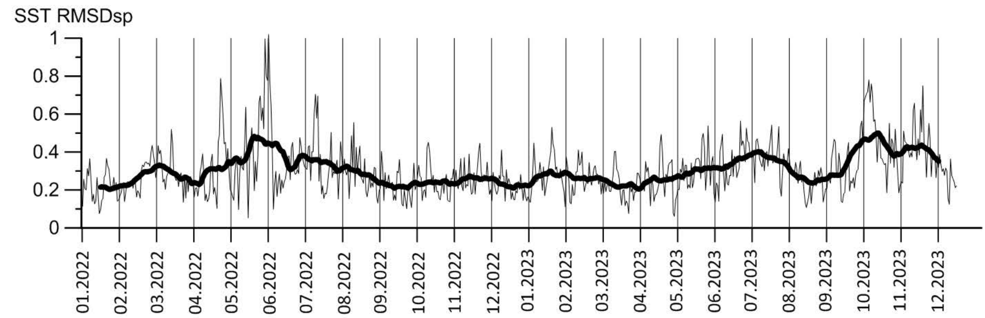
Against the background of clearly pronounced seasonal changes during each separate survey, the SST distribution in the polygon water area exhibited notable spatial heterogeneity. The minimum ranges of the SST spatial changes at the polygon not exceeding 1.5–2 °C were observed at the end of August 2022 (2nd stage of the 123rd cruise) (Fig. 2, *e*) and in the second half of March and early April 2023 (126th cruise) (Fig. 2, *h*), when the warmest and coldest surface waters, respectively, were observed over the entire water area. The maximum SST spatial changes reaching 4–4.5 °C were observed at the polygon in April – May (121st cruise) and December (125th cruise) 2022 and in the first half of October 2023 (1st stage of the 129th cruise), when intensive heating and cooling of surface waters occurred (Fig. 2, *a*, *g*, *k*).

The changes in the SST revealed at the polygon during each separate survey under conditions of non-synchronous survey execution can be considered a superposition of spatial and temporal variability. In order to accurately assess the correlation between the levels of different types of variability, continuous daily averaged data derived from satellite measurements were employed. Fig. 3, *a* shows the SST distribution from satellite data for the period from 1 January 2022 to 31 December 2023 along a 50 m isobath across the entire polygon. A comparison of the SST values derived from *in situ* and satellite data for the same day in grid nodes situated in close proximity to the coordinates of hydrological stations revealed a strong correlation between the change in the SST from *in situ* data and from satellite data during the measurement period (Fig. 3, *b*). The linear relationship coefficient *R*



F i g . 3 . Distributions of SST daily averaged values based on satellite data from 1 January 2022 to 31 December 2023 along the 50 m isobath (the periods of surveys are highlighted by black rectangles) (*a*), satellite SST daily averaged values on separate meridians (blue curves) and in situ SST values at these meridians on the same day (red dots) (*b*), a graph of the linear relationship between the satellite (SSTsat) and in situ (SSTis) temperature series (the dashed lines – 99% confidence interval boundaries) (*c*) between the series of satellite and *in situ* SST values reached 0.99 (Fig. 3, *c*) with statistical significance level $\alpha = 0.01$ (99% level of statistical confidence).

High spatiotemporal resolution of the satellite SST data and good agreement between the *in situ* and satellite SST values allow the latter to be used to assess the relationship between temporal and spatial temperature variability at the polygon. Fig. 4 demonstrates the distribution of the values of spatial RMS deviation of the SST (SST RMSDs) for each day and temporal RMSD of the SST (SST RMSDt) calculated at each grid node with a step of 0.01° along the 50 m isobath for the period from 1 January 2022 to 31 December 2023. The daily averaged values of spatial SST RMSDs throughout the time period varied from 0.1 to 1.0 °C (Fig. 4, *a*). The increase in the level of the SST spatial variability from satellite data (up to 0.7–0.8 °C) in the second half of April 2022 and the first half of October 2023 (Fig. 5, *a*) is consistent with *in situ* measurements. High spatial heterogeneity of the SST field was also observed in April – May 2022 (121st cruise) and October 2023 (1st stage of the 129th cruise) (Fig. 2, *a*, *k*).



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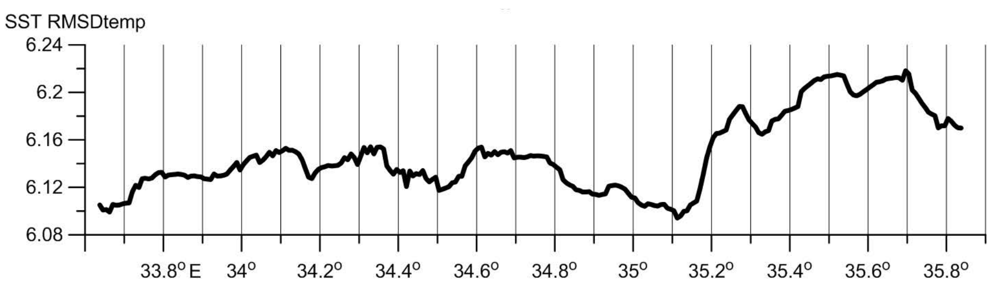


b

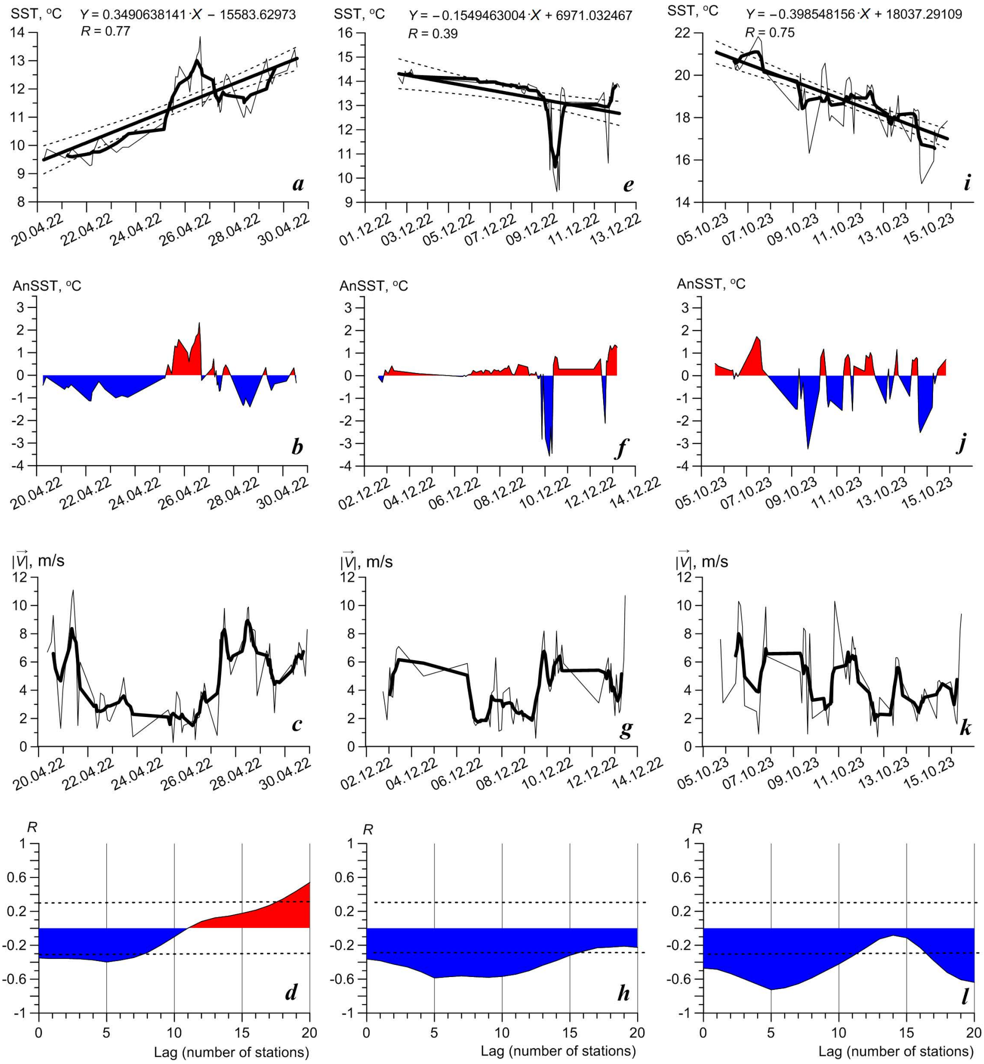
F i g . 4 . Distributions of daily averaged values of spatial SST RMSD (heavy curve – smoothing by a 31-day moving average) (*a*) and values of temporal SST RMSD for the period from 1 January 2022 to 31 December 2023 (*b*) along the 50 m isobath within the measurement polygon based on the satellite data

Distribution of the SST RMSDt values from satellite data indicated that they exhibited minimal spatial variability. For instance, the observed variations within the polygon range from 6.10 to 6.22 °C along the 50 m isobath (Fig. 4, *b*). The highest SST RMSDt values (exceeding 6.16 °C) were observed in the eastern region adjacent to Cape Meganom, within the coastal shelf extension zone.

Thus, the satellite data analysis has revealed that the level of the SST temporal variability is almost an order of magnitude higher than the level of its spatial variability in the water area of the polygon. Spatial homogeneity of the distribution of the SST values at the polygon for each day and high consistency of satellite data with *in situ* measurement data give grounds to believe that the changes in the SST in the water area detected from *in situ* measurement data during each separate survey are mostly related to the SST temporal variability caused by synoptic and seasonal fluctuations.

It is observed that the impact of intra-day variability on the SST distributions was insignificant, as evidenced by data from multi-hour stations. During the daytime, when *in situ* measurements were conducted, changes in the SST did not exceed 0.5 °C while its seasonal fluctuations reached 16.6–18.2 °C. Additionally, the SST variations at the polygon during the intervals of separate surveys ranged from 1.5 to 4.5 °C.

Let us examine the specific characteristics of the SST distribution in greater detail, with a focus on how it varies depending on the time of stations being carried out during the periods of those surveys when the maximum temperature changes at the polygon were observed, namely April – May (121st cruise) and December (125th cruise) 2022 and the first half of October 2023 (1st stage of the 129th cruise) (Fig. 5, *a*, *e, i*). Based on the data of the 121st cruise in April – May 2022, the SST distribution was characterised by a significant increase of its values at the stations from west to east. This increase was reflected in a positive trend significant at the 95% level of statistical confidence ($\alpha = 0.05$) which shows intensive surface water heating, i.e. the manifestation of the seasonal signal during the survey period (Fig. 5, *a*). Note that measurements in the eastern part of the polygon were made almost two weeks later than in its western part. Distribution of the SST anomalies (AnSST) reflecting shorter-period fluctuations of synoptic scale relative to trend showed an alternation of the SST decreasing and increasing events with a period of 3–4 days in April – May 2022 (121st cruise). At the outset and conclusion of the survey, negative anomalies of the SST in relation to the prevailing trend (up to 1.5 °C) were observed and during the midpoint of the period, high positive anomalies (up to 2.5 °C) were recorded (Fig. 5, *b*). It should be noted that the period of measurements revealed no sharp local decrease of the SST by several degrees accompanied by salinity increase, which is typical for upwelling [34, 35]. Furthermore, an examination of meteorological data revealed the absence of discernible atmospheric irregularities that could have potentially influenced the observed changes in the SST (e.g., prolonged intense precipitation, cold atmospheric intrusion with a pronounced decline in air temperature, passage of cyclones) during the course of this cruise. The aforementioned facts indicate that, under these conditions, the primary influence on the changes in the SST on the synoptic scale was exerted by the local wind which caused the mixing of the surface water layer.



F i g . 5 . Distributions of SST (fine lines) at stations depending on the time of their execution (bold lines – linear trend) (*a*, *e*, *i*); SST anomalies relative to the trend (*b*, *f*, *j*); wind speed modulus (*c*, *g*, *k*); cross-correlation functions between SST values and the wind speed modulus (*d*, *h*, *l*) according to the data from the 121st (*a* – *d*), 125th (*e* –*h*), 1st stage of the 129th (*i* – *l*) cruises. Heavy curves – smoothing by moving average over 7 stations, dashed curves – 99% confidence interval boundaries

According to the distribution of near-water wind speed modulus $|\bar{\boldsymbol{V}}|$ (Fig. 5, *c*), periods with positive SST anomalies corresponded approximately to the periods of wind weakening and, vice versa, wind strengthening led to the appearance of negative SST anomalies. In order to quantify the relationship between changes in the SST and changes in wind speed at the stations, the mutual correlation functions between the SST values and wind speed modulus were calculated with statistical significance level $\alpha = 0.01$ (99% level of statistical confidence). It should be noted that the series of the SST and wind speed were formed depending on the station number without taking into account the difference in the time intervals between the execution of neighbouring stations, which can have affected the accuracy of the calculated cross-correlation function. This discrepancy can be attributed to the fact that the distance between neighbouring stations at the polygon is, in the majority of cases, approximately the same. However, the time interval between the execution of neighbouring stations can vary considerably, up to several hours. Consequently, the calculation requires the same shift step. Analysis of the cross-correlation function between the SST values and wind speed modulus showed that the highest level of feedback with correlation coefficient R up to –0.35 was observed at the phase shift near five stations (Fig. 5, *d*). The average time for five stations to be carried out is 10–12 h, since the average time for neighbouring stations to be carried out, calculated as the ratio of the total number of hours in the measurement period to the number of stations to be carried out, is 2–2.5 h. A similar delay of about 10–12 h in the SST response to wind speed changes was obtained from data from the 122nd and 123rd cruises in the summer of 2022 [30].

In December 2022 (125th cruise), a relatively weak but significant negative trend was observed in the SST distribution, which was attributed to seasonal cooling of the waters (Fig. 5, *e*). In the second half of the survey period, when measurements were made in the shallow part of the polygon east of Cape Meganom (Fig. 2, *g*), high negative SST anomalies (up to 3.5 °C) were observed (Fig. 5, *f*). During this period, south and south-westerly winds prevailed (180–225°), which, given the configuration of the coastline, had the nature of negative surge and could have caused the development of upwelling. At the same time, the analysis of vertical temperature and salinity distributions at the stations in the area of the SST decrease showed that this decrease was not traced deeper than 25 m, with the waters of decreased temperature being characterised by the minimum salinity. If the observed decrease in the SST was caused by upwelling, namely the rise of deeper, colder and saltier waters, the area would be expected to show an increase in salinity throughout the subsurface rather than a decrease. It seems reasonable to conclude that the observed decrease in the SST was caused by the mixing of the upper layer which occurred as a result of a significant increase in wind speed (Fig. 5, *g*). Upon conclusion of the measurement period, a positive SST anomaly (up to 1.3 °C) was identified in the vicinity of the eastern boundary of the polygon, accompanied by a notable decrease in wind speed (Fig. 5, *f*, *g*). Similarly to the findings of the 121st cruise data, a significant relationship was identified between the SST and wind speed modulus with a delay in the response of the SST to wind speed changes of approximately 10–12 hours. The maximum values of coefficient R reached –0.6 indicating a strong correlation between two variables (Fig. 5, *h*).

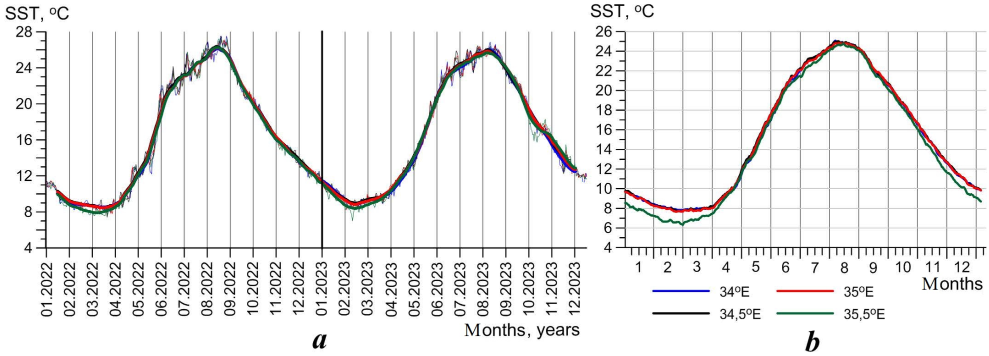
In the first half of October 2023 (1st stage of the 129th cruise) (Fig. 5, *i*), a well-defined negative trend was observed in the SST distribution characterising surface water cooling. Alternation of positive and negative SST anomalies relative to the trend was observed (Fig. 5, *j*). Maximum negative anomalies (−2.5...−3.3 °C) were observed in the coastal zone to the east of Cape Ayu-Dag and in Feodosiya Bay, while maximum positive anomalies (up to 1.5 °C) − at the sea station on the traverse of Cape Ay-Todor (Fig. 5, *j*). Wind speed modulus distribution (Fig. 5, *k*) also demonstrated alternation of periods of wind speed strengthening and weakening on the synoptic scale, corresponding to the periods of the SST decrease and increase, with a maximum *R* value of −0.7 at a shift of about 10−12 h (Fig. 5, *l*).

Therefore, it was established that the SST variability observed at the polygon during each individual survey was attributable to two distinct factors: firstly, the manifestation of seasonal changes on the intra-monthly scale at non-synchronous measurements; and secondly, the SST synoptic variations caused by changes in the local wind speed.

Despite the fact that *in situ* measurements were carried out in all seasons, they are discrete in nature with large time intervals between surveys. The presented data are insufficient to illustrate the continuous evolution of the SST field. Furthermore, they do not indicate the specific phase of the intra-annual SST cycle during which the voyage measurements were conducted. To clarify these features, continuous series of daily averaged data of satellite measurements were analysed.

The spatial homogeneity of the distribution of the SST daily averaged values from satellite data determines the quasi-synchrony of its intra-annual changes in the water area of the entire polygon. This is illustrated by the SST seasonal cycle in different areas of the water area under study obtained from daily averaged values for the period from 1 January 2022 to 31 December 2023 and from daily averaged climate values for the period from 1 January 2008 to 31 December 2023. The SST intra-annual distributions in different water areas demonstrate that the SST intra-annual cycle in 2022 and in 2023 (Fig. 6, *a*) and its climate intra-annual cycle (Fig. 6, *b*) exhibit insignificant variation within the polygon. Some differences were found only for the SST climate values which decrease by almost 1.5 °C during the period of surface water cooling from December to March in the eastern part of the polygon (35.5°E) compared to the rest of the water area (Fig. 6, *b*). Lower surface water temperatures over an extensive shelf in the eastern part of the polygon were also observed from *in situ* data in December 2022 (Fig. 2, *g*) and in late March – early April 2023 (Fig. 2, *h*). The SST minimum climate values (6.5–8 °C) are observed from mid-February to mid-March, the SST maximum ones (25 °C) – in mid-August (Fig. 6, *b*).

Comparison of the SST seasonal cycle in 2022 (Fig. 6, *a*) with its climate seasonal cycle (Fig. 6, *b*) revealed that the SST minimum and maximum in that year were observed in the second half of March and in late August, respectively. This is approximately two weeks later than the climate data would suggest. The SST maximum (27.5 °C) and minimum (8–9 °C) values were higher than the climate ones

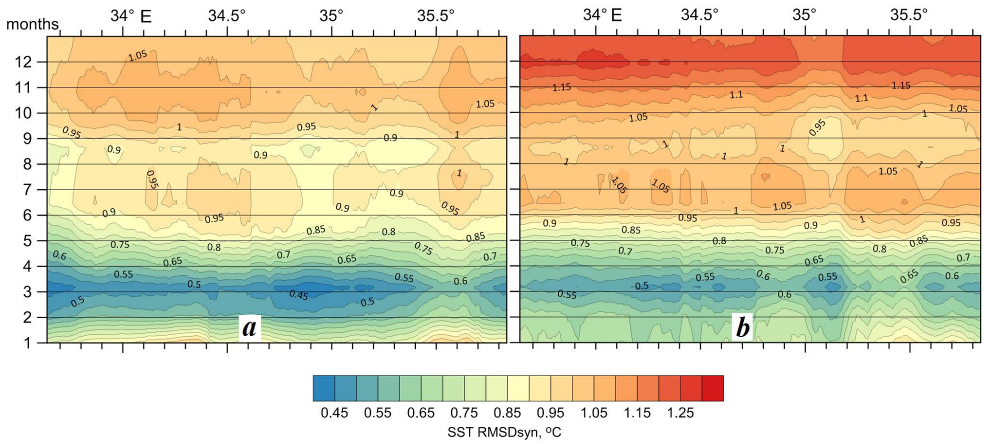


F i g . 6 . Distribution of SST daily averaged values for the period from 1 January 2022 to 31 December 2023 (*a*) and its daily averaged climate values from 1 January to 31 December (*b*) at different meridians at grid nodes located above the 50 m isobath according to the satellite data. Heavy curves on fragment *a* are smoothed by a 31-day moving average

by almost 2.5 and 1–1.5 °C, respectively (Fig. 6). It is noteworthy that the data from the *in situ* measurements indicate that the SST maximum values were also observed in the second half of August in 2022, reaching 27.5 °C (Fig. 2, *d*, *e*).

In 2023, the time of occurrence of the SST minimum according to satellite data corresponded to the climate values. Furthermore, the SST values were found to be 1–1.5 °C higher than the climate ones, with an average of 8–9 °C (Fig. 6). The maximum SST values (26.5 °C) were observed in late July – early August, approximately two weeks earlier than according to climate values, and were almost 1 °C lower than in 2022 and 1.5 °C higher than the climate values (Fig. 6).

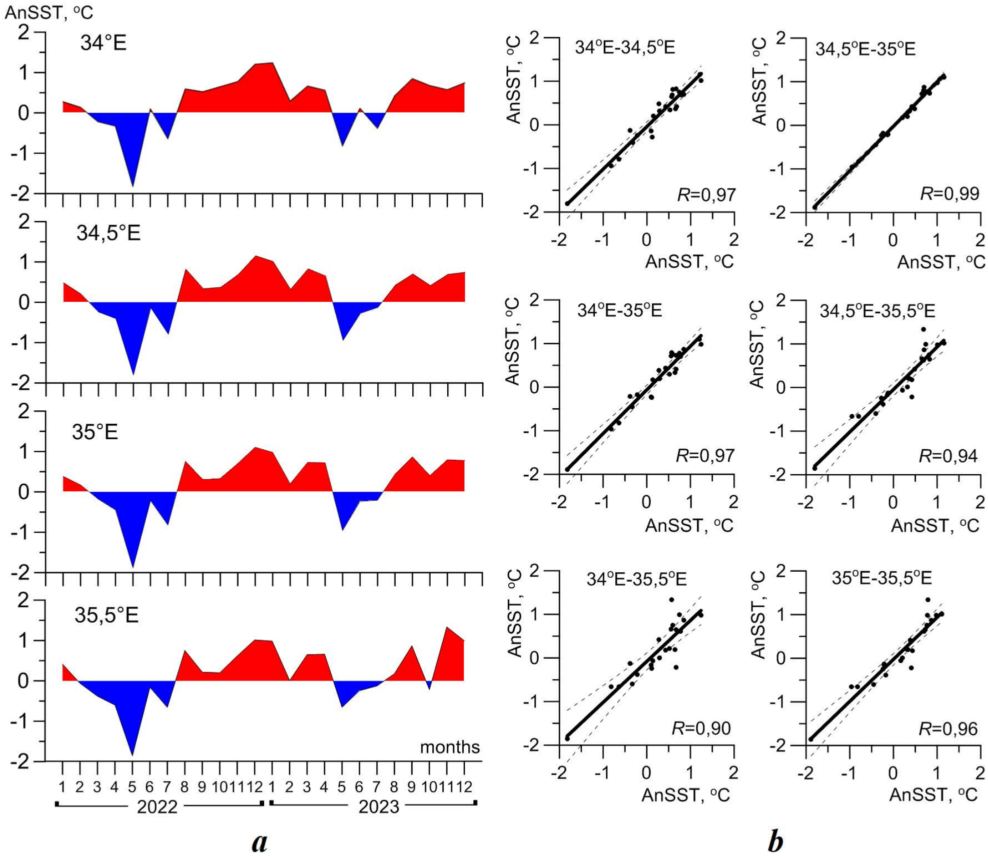
Daily averaged satellite data enabled an assessment of the SST synoptic (intra-month) variability in both 2022 and 2023 as well as identification of differences from the climate norms. According to [7, 22], climate annual cycle of the level of the SST synoptic variability, i.e. the SST RMSD values on a synoptic scale (SST RMSDsyn), in the northern Black Sea is characterised by a semi-annual periodicity with maxima in May (main maximum) and October and minima in February – March (main minimum) and August. Our data indicate that the SST RMSDsyn main maximum values occurred in November 2022 (1–1.1 °C) (Fig. 7, *a*), rather than in May, as indicated by the climate data, and in 2023 – in December (1.2–1.25 °C) (Fig. 7, *b*). The second, weaker increase in the level of the SST synoptic variability in 2022 and 2023 was observed not in October, as in the climate data, but in July, with the SST RMSDsyn values reaching 0.95–1.05 °C in 2022 and 1–1.1 °C in 2023 (Fig. 7). It is noteworthy that the SST variability high range at the polygon in the first half of October 2023 revealed by the *in situ* measurements (Fig. 2, *k*) is consistent with the increase in the level of the SST synoptic variability in October 2023 from satellite data (Fig. 7, *b*).



F i g . 7 . Intra-annual variation of the SST RMSDsyn values based on the satellite data in 2022 (*a*) and 2023 (*b*) along the 50 m isobath within the survey area

In 2022 and 2023, the SST RMSDsyn minimum values (0.4–0.5 °C) were observed in March. The second decrease in the level of synoptic variability was observed in August – September (SST RMSDsyn ~ 0.85–0.9 °C in 2022 and 0.9–0.95 °C in 2023) (Fig. 7). In general, the periods of lowering of the level of the SST synoptic variability, as indicated by satellite data, corresponded to the climate intra-annual cycle and periods of maximum cooling and heating of surface waters in 2022 and 2023. According to *in situ* measurements, the minimum ranges of the changes in the SST at the polygon associated with synoptic variations were also observed in late August 2022 and in the second half of March – early April 2023, when the warmest and coldest surface waters, respectively, were observed throughout the water area (Fig. 2, *e*, *h*).

In addition to the peculiarities of seasonal and synoptic variability, continuous series of satellite data enabled the assessment of the interannual changes in the SST over a two-year period. Given that the SST interannual variability level in the area under study is comparable to that of its synoptic variability [7], the daily averaged SST values were taken on a monthly basis for each month of both 2022 and 2023. This allowed for the minimisation of the manifestation of synoptic variability. Subsequently, the SST monthly averaged anomalies (AnSST) for 2022 and 2023 were calculated as the difference between the actual SST value and the SST climate annual averaged value for the specified month. Distribution of these anomalies, excluding the manifestation of seasonal and synoptic variability, made it possible to identify the differences of monthly averaged SST values in 2022 and 2023 from the climate norm and to assess the SST interannual variations. The AnSST distributions in different areas of the polygon showed that interannual changes in the SST as well as its intra-annual cycle are qualitatively similar throughout the water area (Fig. 8, *a*). Estimates of the linear relationship of the AnSST series at different grid nodes showed their high spatial consistency with correlation coefficients R ~ 0.90–0.99 with statistical significance level $\alpha = 0.01$ (Fig. 8, *b*).



F i g . 8 . Distribution of AnSST from January 2022 to December 2023 at separate grid nodes above the 50 m isobath (*a*), graphs of the linear relationship between AnSST series on different meridians (the dashed lines – 99 % confidence interval boundaries) (*b*)

The AnSST distributions demonstrated that the discrepancies between the SST monthly averaged values derived from satellite data between 2022 and 2023 and the climate norms reached a magnitude of nearly 2 °C. The SST values were observed to exceed the climate values during the period from January to February 2022, from August 2022 to April 2023 and from August to December 2023. The SST maximum positive anomalies (1–1.3 °C) were observed in December 2022 and January 2023 as well as in November – December 2023 (Fig. 8, *a*). The SST values were lower than the climate ones only from March to July 2022 and from May to July 2023. The SST maximum negative anomalies (in their magnitude) observed during the 2022 and 2023 periods were recorded in May, with the values in 2023 (–0.7...–1 °C) exhibiting a decrease of approximately 100% compared to those observed in 2022 (−1.8...−2 °C) (Fig. 8, *a*). In general, the series of the SST monthly averaged anomalies for 2022−2023, with a predominance of their positive values, reflect a trend towards the higher SST during the last two years (Fig. 8, *a*).

Conclusions

The SST variability on different time scales was estimated based on the hydrological measurements made off the Crimean coast of during 2022–2023 cruises of R/V *Professor Vodyanitsky* and *Copernicus* satellite data. The results of the survey demonstrate that the SST minimum values were recorded in April and May 2022 and March and April 2023. Conversely, the SST maximum values were observed in late August 2022 and late June – early July 2023. The SST intra-annual amplitude was 18.2 °C in 2022, while in 2023 it was 16.6 °C.

The data demonstrate that the minimum ranges of changes in the SST at the polygon (1.5–2 °C) were recorded in late August 2022 and in the second half of March – early April 2023, when the warmest and coldest surface waters, respectively, were observed throughout the water area. The maximum changes in the SST (up to 4–4.5 °C) were observed in April – May and December 2022 and in the first half of October 2023, when intensive heating and cooling of surface waters occurred.

It is demonstrated that the SST field spatial heterogeneity was associated with seasonal heating or cooling of water, which manifested on the intra-monthly scale, and with the SST synoptic variations determined by local atmospheric conditions. The SST increase (decrease) periods on the synoptic scale were found to correspond to periods of weakening (strengthening) of the local wind, with the SST response to wind speed changes delayed by 10–12 h.

A high level of agreement between the SST satellite and *in situ* measurements was observed, as indicated by correlation coefficient R ~ 0.99. The present study revealed notable differences in the intra-annual cycle of the SST daily averaged values from satellite data in 2022 and 2023 when compared to the climate norms. In 2022, the SST minimum and maximum values were higher than the climate ones by almost 2.5 and 1.5 °C, respectively, and were observed about two weeks later than according to climate data. In 2023, the SST maximum and minimum values were higher than the climate ones by almost 1.5 °C; at that, the time of occurrence of the SST minimum corresponded to the climate data and the SST maximum was observed approximately two weeks earlier than according to the climate data.

The intra-annual cycles of the level of the SST synoptic variability were found to deviate from the climate norm. In 2022, the main maximum was observed not in May, as follows from the climate data, but in November, while in 2023 – in December. The second increase in the level of synoptic variability in 2022 and 2023 occurred in July, not October, as indicated by the climate data. The periods of decreased level of the SST synoptic variability in 2022 and 2023 corresponded to the climatic intra-annual cycle and were observed in March (main minimum) and August – September. In accordance with the data obtained from *in situ* cruise measurements, the SST minimum synoptic variations were also observed in late August 2022 and in the second half of March – early April 2023.

The satellite data indicate that the SST monthly averaged anomalies relative to the climate norms were predominantly positive from 2022 to 2023. The SST maximum positive anomalies (1–1.3 °C) were observed from December 2022 to January 2023 and in November – December 2023.

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Aleksandr V. Fedirko – development and debugging of software for experiment data secondary processing, computer implementation of algorithms, chart and diagram construction, participation in discussion of the article

All the authors have read and approved the final manuscript.