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Original article

Synoptic Variability of Water Temperature off the Crimea Coast in Summer 2022 Based on the Contact and Satellite Data

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Abstract
Purpose. The aim of the study is to specify the features in changes of the Black Sea surface water temperature off the Crimea coast on a synoptic scale in summer 2022 based on the contact and satellite measurements of water temperature and surface wind.
Methods and Results. The data of hydrological measurements carried out during the 122nd (June 7–23, 2022) and 123rd (August 16–31, 2022) cruises of the R/V *Professor Vodyanitsky* in the northern part of the Black Sea were used. Sea water temperature was measured by the CTD complex IDRONAUT OCEAN SEVEN 320 PlusM, and the wind speed and direction – by the AIRMAR-220WX ship meteorological station. The study also included the daily averaged satellite-derived data on sea surface temperature taken from the *Black Sea – High Resolution L4 Sea Surface Temperature Reprocessed* with the 0.01° × 0.01° spatial resolution, as well as the data on wind speed taken from the *Global Ocean Hourly Sea Surface Wind and Stress from Scatterometer and Model* with the 0.125° × 0.125° spatial resolution (Copernicus Marine Environment Monitoring Service). Based on the contact and satellite measurements, statistical characteristics of the water temperature and wind speed distributions were calculated. It was shown that the differences in temperature distributions revealed from the data of the two-stage surveys in the above-mentioned cruises had been conditioned by the features of a temperature seasonal cycle and by the synoptic variations of surface wind. A significant inverse correlation was found between the wind speed module and the temperature, the maximum level of which was observed in the western part of the survey area, approximately between Cape Aiya and Cape Sarych.
Conclusions. It is shown that based on the contact and satellite measurement, in summer 2022, the values of synoptic temperature anomalies on the sea surface were the highest in the area of noticeable coastal shelf expansion, i.e., in the Feodosiya Bay and between Sarych and Ayu-Dag capes. The temperature synoptic changes were conditioned mainly by the variations in the local wind speed.

Keywords: Crimea coast, Feodosiya Bay, synoptic variability, sea surface temperature, wind field

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Introduction

Numerous studies of synoptic variability in the Black Sea mainly analyze changes in the characteristics, position and number of anticyclonic and cyclonic eddies that form in the Black Sea Rim Current zone and play an important role in the water exchange between the deep-water part and the coastal shelf [1, 2] [1–17]. Processing of data from instrumental measurements of currents and remote sensing of the sea surface [2–5, 7–12], as well as mathematical modeling results [13–17], show that synoptic eddies are characterized by high spatiotemporal variability. According to altimetry data and model calculations [6, 9–11, 16, 17], eddy formation is more active in spring-summer season, when the Black Sea Rim Current weakens, and the number of anticyclonic eddies in the coastal zone increases. According to instrumental measurements of currents and hydrological surveys carried out during three R/V *Professor Vodyanitsky* expeditions in 2018 (June 09 – June 30, August 28 – September 20 and November 18 – December 10), it was shown that the Black Sea Rim Current meandering weakened from summer to late autumn – the beginning of winter, which influenced the number and location of synoptic gyres. The maximum number of eddies was observed in summer, the minimum – in autumn-winter period [8].

The 1992–2015 satellite altimetry and hydrological data analysis showed that thermohaline anomalies in eddies of both signs, which characterize synoptic variability, are maximum in summer and weaken in winter [10]. According to [6], the synoptic temperature variability level in the coastal zone is higher than in the open part of the sea and its increase is observed from winter to summer. At the same time, according to the numerical modeling results, the synoptic variability of hydrophysical fields is most pronounced when the Black Sea Rim Current intensifies, i.e., in winter-spring period [15]. In addition to the influence of synoptic eddy formations, synoptic variability of thermohaline fields can be associated with local weather conditions or upwellings. Thus, an analysis of expeditionary observations in the coastal zone of the northeastern Black Sea (near the city of Gelendzhik) revealed that in June – July 2009 there was intense synoptic variability of sea surface temperature (SST) with a time scale of about several days/weeks with a range of 14 °C, caused by the upwelling of cold and salty subsurface waters [18]. According to long-term 1977–2005 observations, at hydrometeorological stations in the northeastern Black Sea [19], the climatic annual cycle of root mean square values of synoptic water temperature anomalies is characterized by their minima in December – February and August and maxima in June – July and September–November. The analysis of satellite SST measurement series from the Black Sea High Resolution and Ultra High-Resolution Sea Surface Temperature Analysis (BS HR UHR SST Analysis) array for 1982–2015 with a high spatial resolution of 0.04° × 0.04° showed that on the northwestern Black Sea shelf, the minimum SST variability on a synoptic scale is observed in February–March, the maximum in May, while the maximum level of variability can be seen closer to the coast [20]. Using the same data, it

[1] Blatov, A.S., Bulgakov, N.P., Ivanov, V.A., Kosarev, A.N. and Tuljulkin, V.S., 1984. *Variability of the Black Sea Hydrophysical Fields*. Leningrad: Gidrometeoizdat, 240 p. (in Russian).

[2] Latun, V.S., 1989. The Role of Anticyclonic Gyres in the Intraseasonal Evolution of Thermohaline Structure and Geostrophic Circulation of Waters. In: S. P. Levikov, ed., 1989. *Investigation and Modeling of Hydrophysical Processes in the Black Sea*. Moscow: Gidrometeoizdat. Section 2.1, pp. 40-49 (in Russian).

was shown that the climatic annual cycle of the synoptic SST variability level for the entire Black Sea water area is the same and is characterized by a semi-annual periodicity with minima in February–March and August and maxima in May and October. The largest contribution of synoptic variability into the overall dispersion of the SST field was observed in the Kerch Strait and over the continental slope south of the Kerch Peninsula and further to the west along the entire southern coast of Crimea [21]. At the same time, the spatial structure of the SST field and its variability in shallow coastal waters off the coast of Crimea on a synoptic scale have been poorly studied. This is primarily due to the large grid spacing of the previously used contact measurement data. During the 122nd and 123rd cruises of the R/V *Professor Vodyanitsky* in summer 2022, some expeditionary studies were conducted. They were of particular interest, since they were carried out in the warm season over a more frequent grid of stations during synoptic activity increase. For the first time, hydrological measurements off the coast of Crimea in the course of each cruise were carried out twice along the same route, which makes it possible to clarify the features of the actual SST variations on a synoptic scale.

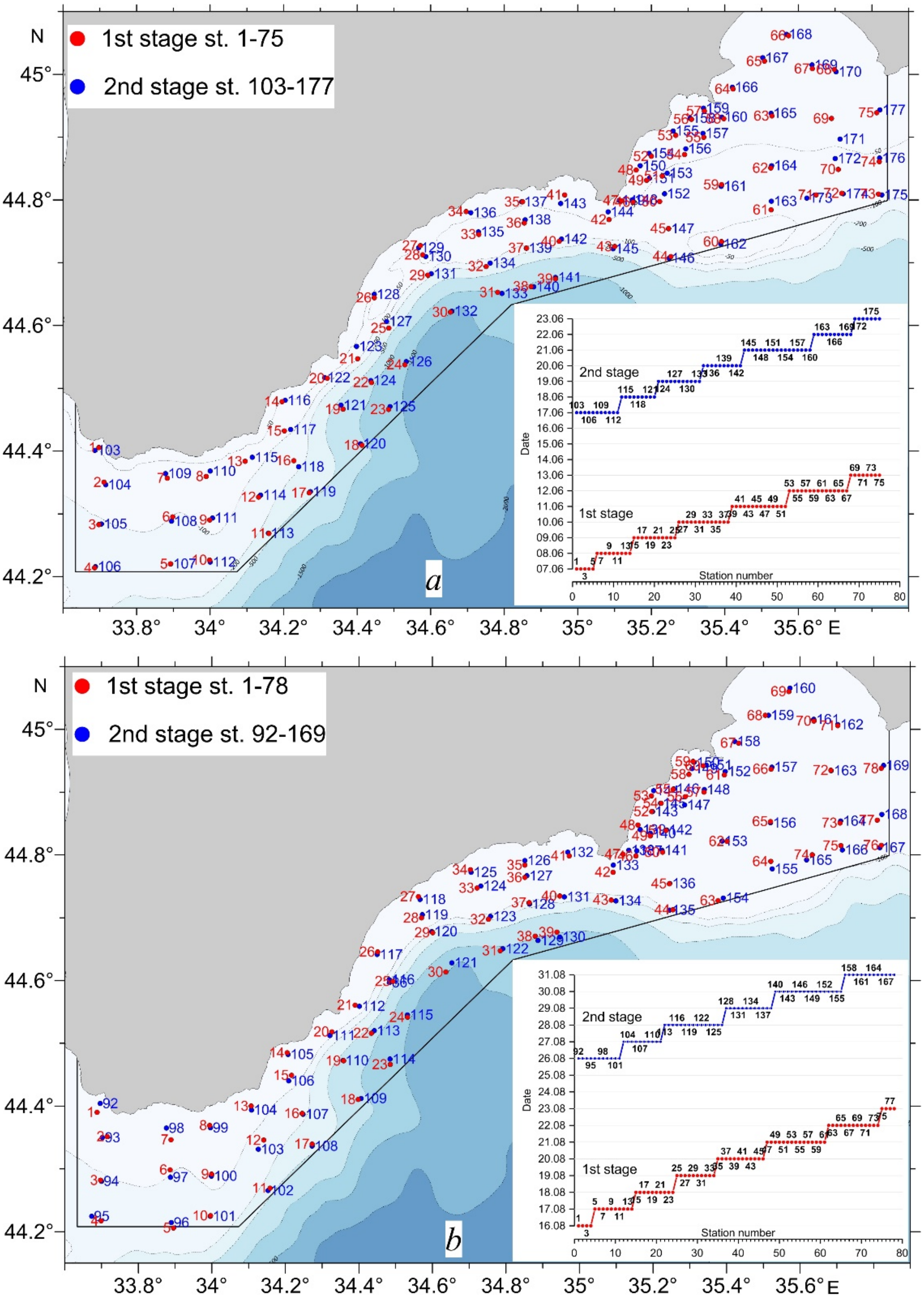
The aim of the present study is to specify the features of temperature changes on the surface of the Black Sea off the coast of Crimea on a synoptic scale and to assess their relationship with changes in the wind field based on contact hydrological measurements made in the course of two expeditions on the R/V *Professor Vodyanitsky* in summer 2022 and *Copernicus* data satellite measurements of temperature and surface wind.

Materials and methods

Hydrological measurements in summer 2022 were carried out in the course of the 122nd (June) and 123rd (August) cruises of the R/V *Professor Vodyanitsky* and, unlike previous years, exclusively within the territorial waters of Russia (Fig. 1). Reducing the survey area while maintaining total expedition time (25 days) made it possible to increase the number of hydrological stations and obtain detailed spatial distributions of hydrological parameters reflecting the current state of the water structure in the coastal zone of Crimea. The expedition time reserve on both cruises enabled to carry out repeated hydrological surveys. Positions of the stations are shown in Fig. 1, *a*, *b*.

In the course of each cruise, the repeated stations were carried out in almost the same coordinates with sequential advancement from the west to the east with approximately the same phase delay (Fig. 1, insets). On the 122nd cruise, the first stage of surveys was carried out from June 7 to June 13, the second – from June 17 to June 23; on the 123rd cruise – from August 16 to August 23 and from August 26 to August 31, respectively.

The sea water temperature was measured at each station using the IDRONAUT OCEAN SEVEN 320 PlusM WOCE-CTD multiparameter probe. Analysis of the SST field distribution was carried out for the upper quasi-homogeneous layer at the 2 m horizon. The actual values of wind speed and direction at the stations were taken from the expedition duty officer journal, which, in turn, were selected from the continuous records made using the onboard AIRMAR-220WX weather station.



F i g. 1. Layout of the stations carried out during the 122nd (*a*) and 123rd (*b*) cruises of the R/V *Professor Vodyanitsky*. Insets show the dates and numbers of soundings

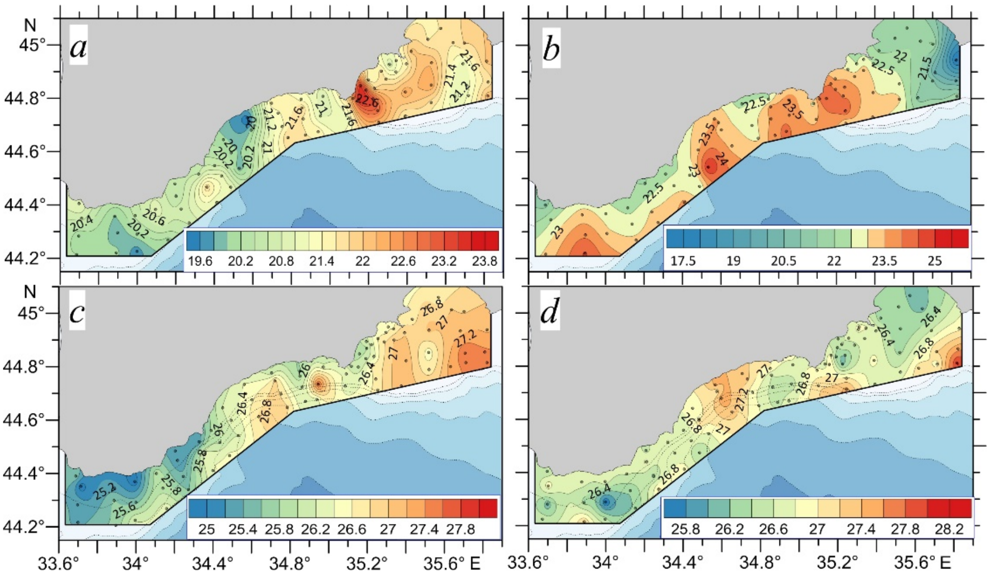
The work also uses mean daily satellite SST measurements from the *Black Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis* array (https://doi.org/10.48670/moi-00159; https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-SST-PUM-010-004-006-012-013.pdf, product SST_BS_SST_L4_NRT_OBSERVATIONS_010_006) of Copernicus Marine Environment Monitoring Service (CMEMS) with ultra-high spatial resolution 0.01° × 0.01° obtained using modern processing algorithms [22].

In addition, the mean daily characteristics of the surface wind field (speed and direction) were analyzed using a spatial resolution of 0.125° × 0.125° from the *Global Ocean Hourly Sea Surface Wind and Stress from Scatterometer and Model* array (https://doi.org/10.48670/moi-00305, product WIND_GLO_PHY_L4_NRT_012_004), included in CMEMS. These parameters were obtained from observations using the Metop-B and Metop-C ASCAT scatterometers and from the operating model of the ECMWF (European Center for Medium-Range Weather Forecasts).

The SST field variability and its relationship with wind speed was studied using standard statistical methods of variance and correlation analysis.

Research results

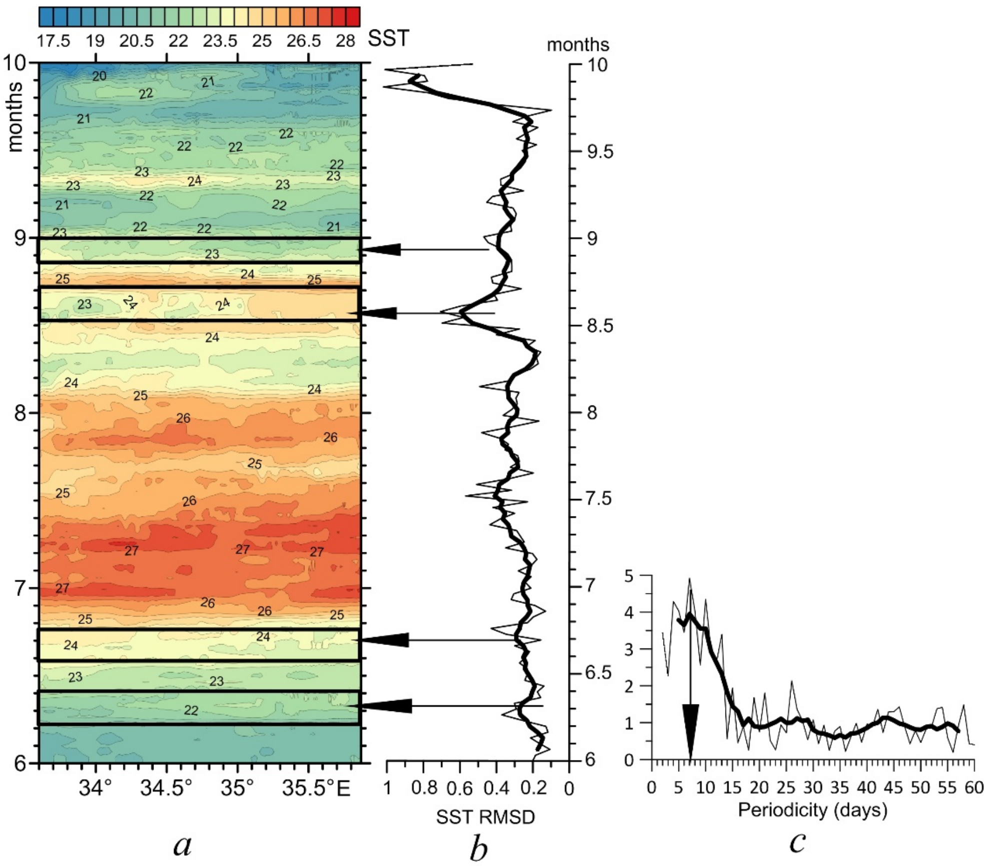
The analysis of SST distributions based on the data from two stages of surveys on the 122nd and 123rd cruises of the R/V *Professor Vodyanitsky* indicates their significant differences. They, on the one hand, are due to seasonal warming of surface waters and, on the other hand, are due to synoptic variations in the surface wind. The seasonal warming was reflected in a general increase in temperature values, which at the first stage of surveying on the 122nd cruise did not exceed 24 °C and at the second stage reached almost 26 °C (Fig. 2, *a*, *b*).



F i g. 2. SST (°C) distribution at the first (*left*) and second (*right*) stages of the 122nd (*a*, *b*) and 123rd (*c*, *d*) cruises of the R/V *Professor Vodyanitsky*

Under summer warming conditions, the spatial distribution of the actual SST was significantly affected by asynchronous surveys. This was manifested in the increase of SST values as the vessel moved from the west to the east, which took

~ 7 days. Since the measurements were taken mainly in the daytime, the influence of the diurnal SST variation on its spatial distributions was minimal.



F i g. 3. Distribution of the satellite derived SST daily average values along the 50 m isobath in June 1 – September 30, 2022 (*a*); temporal distribution of the spatial SST standard deviation (thick curve denotes smoothing by a 5-day moving average) (*b*), functions of spectral density of distribution of the SST standard deviation (*c*) based on satellite data

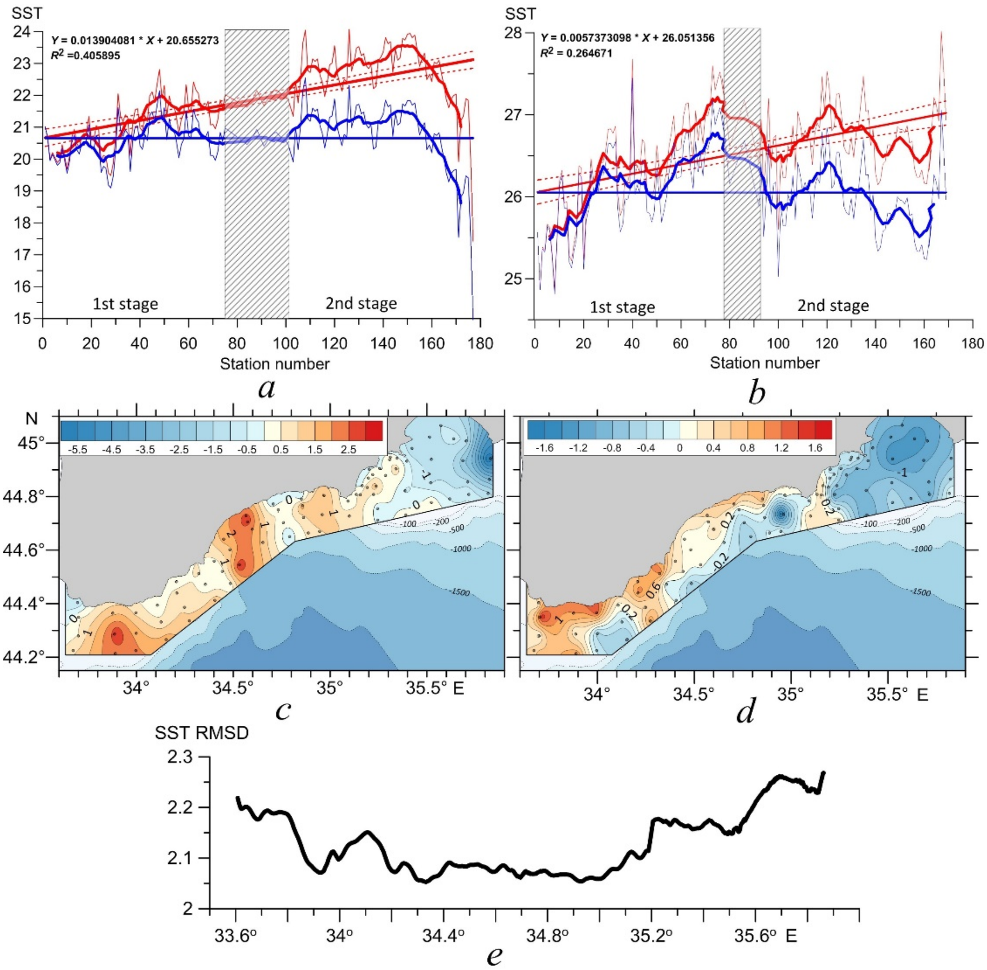
To compare contact measurements with mean daily satellite ones, which almost synchronously covered the entire survey water area, the SST distribution was constructed from satellite data along a 50-m isobath passing through the entire water area of the polygon for June 1 – September 30, 2022 (Fig. 3, *a*, the periods of surveying during the first and second stages of two cruises are highlighted with black rectangles). During the first survey phase of the 122nd cruise, the spatial variability range of actual temperature was almost 4 °C (20–24 °C), while according to satellite data it was only 1.5 °C (21–22.5 °C) (Fig. 2, *a*; 3, *a*). The trend towards the SST increase in the eastern direction, observed from contact measurements, was not evident from satellite data. At the second stage of the survey, the range of spatial variability of the actual temperature according to contact measurements over almost the entire water area was ~ 2 °C (22–24 °C). The exception was the extreme eastern part of the polygon, where actual SST values decreased sharply to almost 20 °C.

According to satellite data, the range of spatial SST variability did not exceed 0.5 °C (23.5–24 °C) (Fig. 2, *b*; 3, *a*).

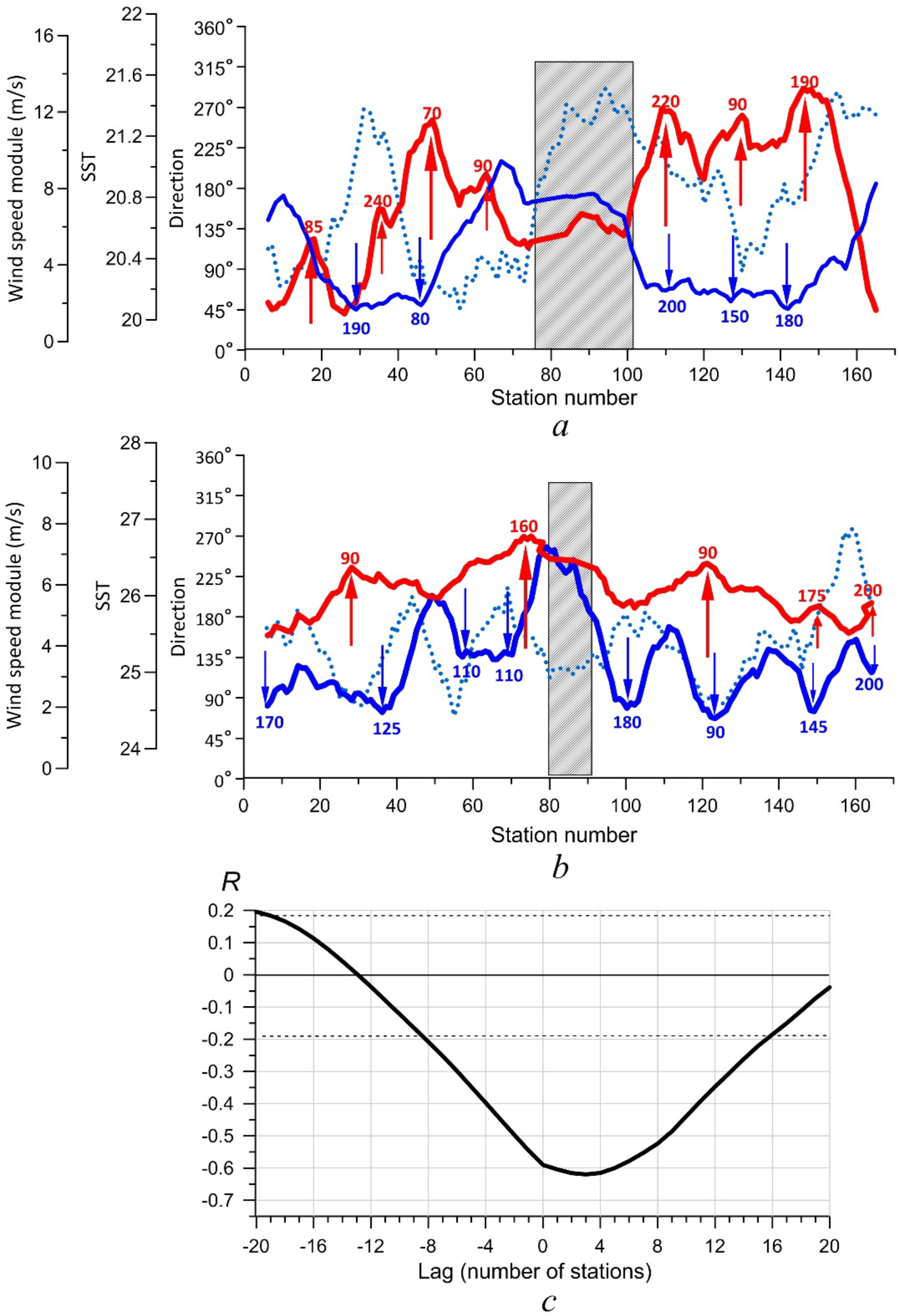
At the first stage of the 123rd cruise two months later, the actual SST values in the water area of the polygon varied within 25–27.5 °C (Fig. 2, *c*), while its maximum values were observed at the end of the stage in the east of the polygon. The SST distribution according to satellite data also showed an increase in temperature to 25.5 °C in the east of the polygon (Fig. 3, *a*). The minimum SST values according to both contact and satellite measurements were observed in the west of the polygon, while according to satellite data (23 °C) they were almost 2 °C lower than according to contact measurements (25 °C). This difference is probably due mainly to the methodological features of processing data from different types of measurements.

At the second stage of the 123rd cruise, the SST values according to contact measurements varied within 26–27.4 °C, which was close to the range of spatial SST variability at the first stage (Fig. 2, *d*). In contrast to the first stage, the lower SST values (< 26.4 °C) were observed not only in the western but also in the eastern part of the survey. In the central part of the polygon and in certain local areas near its southern boundary, the SST increased to 27 °C. According to satellite data, the SST values were noticeably lower and varied within 22–23.5 °C (Fig. 3, *a*). Judging by the longitude-time distribution of SST, during the second stage of the survey the temperature decreased monotonically, i.e., cooling of surface waters was already observed at the end of August (Fig. 3, *a*). Thus, asynchronous contact measurements in the presence of a seasonal signal can significantly affect the spatial distribution of the actual SST. This problem can be partially overcome by detrending the original series of contact measurements allowing to remove the lower-frequency component of variability with a time scale exceeding the survey period. In the presence of a low-frequency signal in the measured SST series, a significant linear relationship should be observed between the SST value at each station and the serial number of this station (time lag of the measurements). The estimates showed that the correlation coefficient R between the SST value and the station serial number reached 0.66 in the 122nd cruise (Fig. 4, *a*) and 0.51 in the 123rd cruise (Fig. 4, *b*), i.e., the distributions of the actual SST contained a significant positive trend. Judging by satellite data, the positive trend in the 122nd cruise (June) was associated with stable seasonal warming of surface waters (Fig. 3, *a*; 4, *a*). In the 123rd cruise (August), periods of warming and cooling of surface waters were observed on a synoptic scale against the background of the general autumn SST decrease. The temporal distribution of the mean daily values of the spatial standard SST deviation according to the satellite data along the 50 m isobath (Fig. 3, *b*) showed that its changes are especially noticeable during the first stage of surveying in the 123rd cruise, when the SST contrasts between the western and the eastern parts of the polygon according to contact (Fig. 2, *c*) and satellite (Fig. 3, *a*) data were most pronounced, which caused a sharp increase in the standard deviation values. Note that the period of each survey stage (6–8 days) approximately coincided with the periodicity observed in the temporal change in the spatial SST standard deviations, i.e., with the periodicity of intensification of synoptic SST disturbances according to the satellite data (Fig. 3, *b*). Calculation of the spectral density distribution function of SST standard deviation from satellite data showed that this periodicity is ~ 7 days (Fig. 3, *c*).

Note that the first stage of measurements in the 123rd cruise took place during the period of SST decrease according to the satellite data in the western part of the polygon and its slight increase in the eastern part. The second stage of measurements took place in the last week of August, when reduced SST values were observed throughout the entire polygon according to the satellite data. Thus, the contact measurements in the 123rd cruise did not always coincide with the warm phase of synoptic SST changes observed from the satellite data (Fig. 3, *b*). At the same time, a general positive trend in SST was observed during the entire survey (Fig. 4, *b*), although it was noticeably less pronounced than at the beginning of summer (122nd cruise), when a steady warming of surface waters was observed (Fig. 4, *a*).



F i g. 4. SST (°C) distribution depending on the station serial number (red curves are the actual temperature, blue ones are the detrended temperature; thick curves are smoothing by a moving average over 11 stations, dashed ones are the boundaries of the 95% confidence interval of statistical significance; the interval between the stations performed during the first and the second stages is shaded) based on the data of the 122nd (*a*) and 123rd (*b*) cruises; difference between the detrended SST values obtained in the repeated surveys of the 122nd (*c*) and 123rd (*d*) cruises; change of the SST standard deviation with a longitude along the 50 m isobath (*e*) based on satellite data



F i g. 5. Distribution of the detrended SST (°C) values (red curves), the absolute value (blue solid curves) and direction (blue dashed curves) of wind speed based on the data of the 122nd (*a*) and 123rd (*b*) cruises of the R/V *Professor Vodyanitsky* (the interval between the stations performed during the first and the second stages is shaded; red arrows show the SST maxima, blue ones – the wind speed minima; numbers beside the arrows indicate wind direction in degrees); graph of the cross-correlation function of SST and wind speed module based on the 122nd cruise data (dashed lines are the boundaries of the 95% confidence interval of statistical significance) (*c*)

To minimize the influence of measurement asynchrony in the seasonal signal presence, the observed positive trend was subtracted from the original SST series. The analysis of SST anomalies, calculated as the difference (ΔT) of detrended temperature values between repeated surveys at each station, made it possible to assess the features of the spatial SST structure, predominantly on a synoptic scale, during periods of warming and cooling of surface waters. In the 122nd cruise, three areas with increased positive ΔT values (> 2 °C) and one with negative ΔT values (> − 2 °C) were observed (Fig. 4, *c*). At the same time, positive ΔT values were observed in most of the survey water area (Fig. 4, *c*), which can be explained by a general weakening of wind speed at the second stage of the survey (Fig. 5, *a*) and an increase in SST values (Fig. 2, *b*). At the end of the survey, there was a sharp increase in wind speed, a decrease in SST values, and an increase in negative ΔT values to almost 6 °C.

In the 123rd cruise, there was an increase in positive ΔT values mainly in the west of the survey (up to 1.5 °C) and negative values (up to – 2 °C) in the east of the survey (Fig. 4, *d*). As in the 122nd cruise, an increase in ΔT values (in absolute value) was observed in areas where the coastal shelf is the widest – in the area of the Feodosiya Bay and off the Southern Coast of Crimea between Cape Sarych and Cape Ayu-Dag. Qualitatively, the same picture can be observed from satellite data, since the standard deviation SST values, calculated from a series of mean daily SST values for four months (June – September 2022) for each longitude with a step of 0.01° along the 50 m isobath, increase noticeably in the areas where the isobath passes over an extensive shelf (Fig. 4, *e*). This gives reason to believe that the level of spatial SST dispersion is influenced by the total width of the shelf, which is manifested even within the survey area (no more than 12 miles from the coast).

As can be seen from Fig. 5, the most important factor determining SST values in shallow water on a synoptic scale is local wind effect. It was previously shown that with a relatively weak daily SST variation, which in the warm season averages less than 0.5 °C, the dominant role in changing the SST field is played by synoptic variations in the surface wind speed [23, 24]. The connection between the wind field and temperature changes was most clearly traced from the survey data of the 122nd cruise. A pattern was revealed – temperature growth periods coincided qualitatively with wind weakening periods and vice versa – increased wind led to a decrease in SST values (Fig. 5, *a*). Analysis of the cross-correlation between SST and the wind speed module according to the 122nd cruise data showed that the highest level of inverse correlation with an R value of up to 0.6–0.65 was observed at a lag of up to 3–4 stations (~ 8–10 h) (Fig. 5, *c*).

On the 123rd cruise, the maximum wind speed decreased noticeably, the periods of decreased SST did not always coincide with the periods of weakened local wind (Fig. 5, *b*), and the correlation between these parameters was insignificant. It can be assumed that the change in SST on the 123rd cruise was influenced to a greater extent by changes not in the local, but in the distant wind.

To assess the relationship between SST and wind speed, mean daily series of satellite data were also analyzed for June 1 – August 31, 2022 along the 50 m isobath within the survey area, while wind speed data were interpolated into temperature grid nodes with a step of 0.01°. A significant negative correlation was revealed between the wind speed module and SST, the level of which varied noticeably over space (Fig. 6, *a*). Thus, high R values (− 0.55 ... − 0.7) were detected in the western part of the polygon approximately between Cape Aiya and Cape Sarych, while the maximum was observed at a lag of 3–6 days with the leading change in wind speed. To the east of Cape Ai-Todor and approximately to Cape Meganom, a sharp decrease in the level of reverse correlation and a change in its sign were observed at lags of 1–3 days. To the east of Cape Meganom, the level of correlation began to increase to significant, and near the Feodosiya Bay the R values reached − 0.45 ... − 0.5 at a lag of 4–7 days (Fig. 6, *a*).

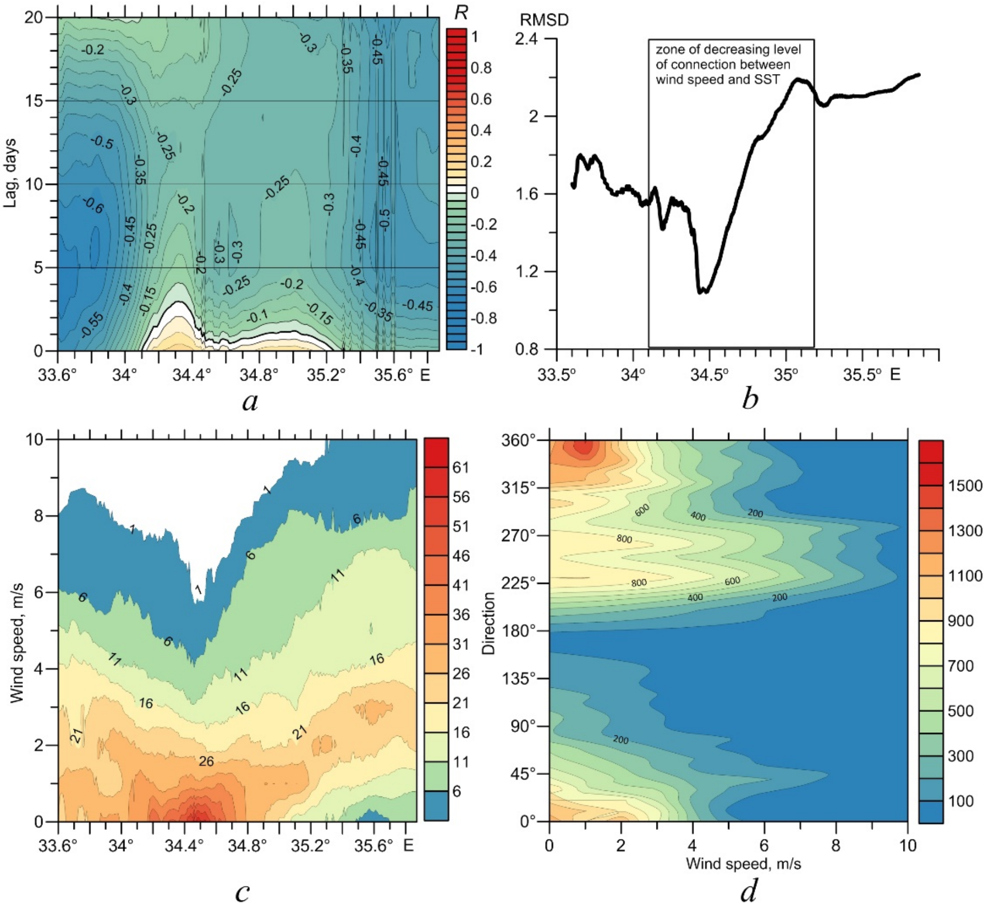


Fig. 6. Distribution of the *R* extreme values of the cross-correlation function of wind speed module and SST (°C) (*a*), standard deviation of the daily averaged values of wind speed module (m/s) (*b*), frequency of the speed module values with a resolution 1 m/s (*c*), frequency (day) of the winds of a certain speed depending on direction (*d*) along the 50 m isobath based on satellite data

Analysis of the standard deviation distribution of the mean daily values of the wind speed module, calculated for summer 2022 at each longitude with a step of 0.01° along the 50 m isobath, showed that the minimum level of wind speed module variability (standard deviation up to 1.4 m/s) was observed in the area of 34.4° and

34.6°E (Fig. 6, *b*), i.e., in the zone of decreasing relation level between wind speed and SST. The maximum values of wind speed standard deviation (up to 2–2.2 m/s) were identified east of 34.9°E (Fig. 6, *b*). At the same time, in the area of the Sudak Bay and Cape Meganom, the relationship between wind speed and SST was insignificant, and in the area of the Feodosiya Bay, where the coastal shelf noticeably expands, a high level of relation between wind speed and SST was observed (Fig. 6, *a*).

The present paper analyzed the frequency of mean daily speed module values with a discreteness of 1 m/s (Fig. 6, *c*) along the 50 m isobath for June 1 – August 31, 2022, as well as the total frequency (number of days) of winds of a certain speed depending on the direction (Fig. 6, *d*). The analysis showed that in the area of insignificant correlation between wind speed and SST, the maximum frequency of minimum speed winds (below 1.5 m/s) (Fig. 6, *c*) in the northern and northwestern directions was observed (Fig. 6, *d*). The maximum frequency of weak winds of the main northern direction in the polygon area is approximately between 34° and 35°E due to the screening effect of the Crimean Mountains.

Conclusion

Based on the contact hydrological measurements carried out during the 122nd (June 7 – June 23, 2022) and 123rd (August 16 – August 31, 2022) cruises of the R/V *Professor Vodyanitsky* and the data from Copernicus satellite measurements of temperature and surface wind, peculiarities of sea surface temperature variability off the coast of Crimea on a synoptic scale were identified. It was shown that the differences in SST distributions according to the data of two stages of surveys in two cruises were due to the peculiarities of the seasonal cycle of surface temperature and synoptic variations in the surface wind. The spatial SST distribution was significantly affected by asynchronous surveying, which was manifested in the SST increase as the vessel moved from the west to the east. It was established that the actual SST distributions during the survey periods contained a significant positive trend. According to the satellite data, a steady seasonal warming of surface waters was observed during the 122nd cruise (June). On the 123rd cruise (August), alternating periods of warming and cooling of surface waters lasting about a week were observed. The contact measurements on this cruise did not always coincide with the increased SST periods, which underestimated its overall positive trend. On the 123rd cruise, the maximum changes in the mean daily values of the spatial SST standard deviation according to the satellite data were also noted.

On the 122nd cruise, positive synoptic SST anomalies were recorded in most of the survey area, which was associated with a general weakening of wind speed and an increase in temperature during the second stage of the survey. The values of SST anomalies according to actual measurements and the values of the SST standard deviation, calculated from its mean daily series for four months (June – September 2022) according to satellite data, increased noticeably in the area of the Feodosiya Bay and near the Southern Coast of Crimea between Cape Sarych and Cape Ayu-Dag, where the coastal shelf is wider.

It was shown that periods of increase in actual temperature coincided qualitatively with periods of local surface wind weakening and vice versa – increased wind led to a decrease in SST values. The highest level of inverse correlation between SST and the wind speed module with an *R* value of up to 0.6–0.65 at a lag of 8–10 hours was recorded on the 122nd cruise. The satellite data also showed the presence of a significant inverse correlation between the wind speed module and SST, the level of which varied noticeably over space. The maximum level of correlation with correlation coefficient values of − 0.55 ... − 0.7 was recorded in the western part of the survey area approximately between Cape Aiya and Cape Sarych. To the east of Cape Ai-Todor and approximately to Cape Meganom, a sharp decrease in the reverse correlation level and a change in its sign were noted. To the east of Cape Meganom, the correlation level began to increase to significant, and near the Feodosiya Bay the correlation coefficient values reached − 0.45 ... − 0.5. In summer 2022, the minimal variability of the wind speed module and the maximum frequency of winds of minimum speed in the northern and northwestern directions were observed in the zone of decreasing relation level between wind speed and SST.

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