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Regional Features of the Temperature Field Synoptic Variability on the Black Sea Surface from Satellite Data

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Purpose. The aim of the work is to clarify the regional features of synoptic variability of the Black Sea surface temperature, to reveal its intra- and inter-annual changes and to assess the features' relations with the large-scale atmospheric processes.
Methods and Results. The satellite-derived data on the sea surface temperature in 1982–2018 from the *Copernicus* array were used; their temporal resolution was daily average and the spatial one – 0.04 degrees. These data showed that the maximum of temperature synoptic variability was observed in the coastal part of the northwestern shelf from the Dnieper-Bug estuary to the Danube delta, in the Karkinit Bay and in the Kerch Strait. In the deep sea, strong synoptic variability can be observed in the regions of the Eastern cyclonic gyre and the Batumi anticyclone. The greatest contribution of synoptic variability to the total temperature dispersion was observed in the Kerch Strait and to the south of the Kerch Peninsula. The level of multi-year average synoptic variability is lower or comparable with the level of the interannual variability in most of the water area, except for the Kerch Strait, the northwestern and the Bosporus shelves. It is revealed that in the climatic annual cycle the main maximum of synoptic variability is observed in May, a month before the maximum rate of surface water heating is achieved, the second maximum – in October, a month before the maximum rate of water cooling. The minimums are observed in February–March, during the period of maximum cooling of surface waters, and in August, during their maximum heating. Noticeable interannual changes of the level of temperature synoptic variability varying from −0.3 °C to 0.3 °C, were revealed.
Conclusions. Synoptic variability of the Black Sea surface temperature is characterized by noticeable intra-annual and interannual variations. Its climatic annual cycle is of a semi-annual periodicity due to the processes of water cooling and heating. The maximum increase of the synoptic variability level on the interannual scale is observed after 2003 on the northwestern shelf. Significant correlation with the indices of the North Atlantic, East Atlantic and the East Atlantic–West Russia oscillations was not revealed.

Keywords: Black Sea, sea surface temperature, satellite measurements, synoptic and interannual variability, atmospheric circulation indices.

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Introduction

Modern problems associated with the rational use of the Black Sea resources and its ecosystem conservation require further refinement of the spatio-temporal variability of the water structure. The most representative monitoring of sea surface temperature (SST) variability is carried out using satellite measurements with high spatial and temporal discreteness. In modern publications, the main attention is paid to SST variability on time scales from seasonal to inter-decadal one. The dominant role of seasonal variations in the total spectrum of the Black Sea SST variability was shown [1–5], tendencies of interannual SST variability and its relationship with large-scale atmospheric processes were estimated [1–11].

In addition to seasonal and interannual scale processes, synoptic processes play an important role in the thermohaline structure and dynamics variability of the Black Sea waters [4, 12–19]. Some estimates of the Black Sea synoptic and mesoscale variability characteristics based on the analysis of various types of experimental data, the results of mathematical modeling and satellite measurements can be found in [4, 13, 17–19]. It was shown that, in general, the level of synoptic temperature variability in the coastal zone is higher than in the open part of the sea, while its increase from winter to summer is observed [4]. At the same time, the authors note that due to the insufficient number of long multi-day stations, it is impossible to reliably assess the characteristics of the intra-annual cycle of synoptic variability in the open part of the sea. An analysis of the spatial features of the distribution of the SST synoptic variability level along the northern part of the Chersonesus – Bosphorus section showed that to the north of the climatic position of the Rim Current (RC) jet, the level of synoptic variability decreases, while directly in the RC jet it increases markedly [17]. According to the numerical simulation data, the synoptic variability of hydrophysical fields is most pronounced when the RC intensifies, i.e., in the winter-spring period [18]. According to SST satellite measurements, it was found that on the northwestern shelf, the minimum synoptic variability of SST is observed in February – March, and the maximum – in May [19].

In this work, based on a modern array of satellite SST data with a high spatial-temporal resolution, the regional features of the synoptic temperature variability on the Black Sea surface, its intra-annual and interannual changes are clarified, and their relationship with large-scale atmospheric processes is estimated.

Materials and methods

The data of SST satellite measurements for 1982–2018 from the *Black Sea – High Resolution L4 Sea Surface Temperature Reprocessed* (http://marine.copernicus.eu/ interactive catalogue/SST_BS_SST _L4_REP_OBSERVATIONS_010_022) array, obtained using the high-resolution radiometer AVHRR Pathfinder Version 5.2 (PFV5.2) of the National Oceanographic Data Center NOAA, were used in the present work. The regular mean daily satellite SST data used at the 0.04° × 0.04° grid nodes were obtained by a single technique for the entire sea area using modern processing algorithms [20, 21]. According to [22], a time period of more than 35 assessing the interannual variability trends, and the average daily resolution makes it possible to analyze the synoptic variability of SST on an intramonthly scale.

To analyze the synoptic variability level and assess its relationship with other types of variability at each grid node, the total, interannual and synoptic (intramonthly) root mean square deviations (RMSD) of the SST were calculated.

Total SST $RMSD_{syn}$ was calculated over the entire 37-year time series of daily mean SST values. The level of interannual SST variability was estimated by the $RMSD_{interann}$ calculated from the time series of 37 monthly average SST values for January, February, etc., which were then averaged over all 12 months. The intra-month RMSDs were calculated by the average daily SST series for each month of each year and then averaged over 37 years for January, February, etc. (climatic $RMSD_{syn}$) and for all 444 months (mean long-term $RMSD_{syn}$).

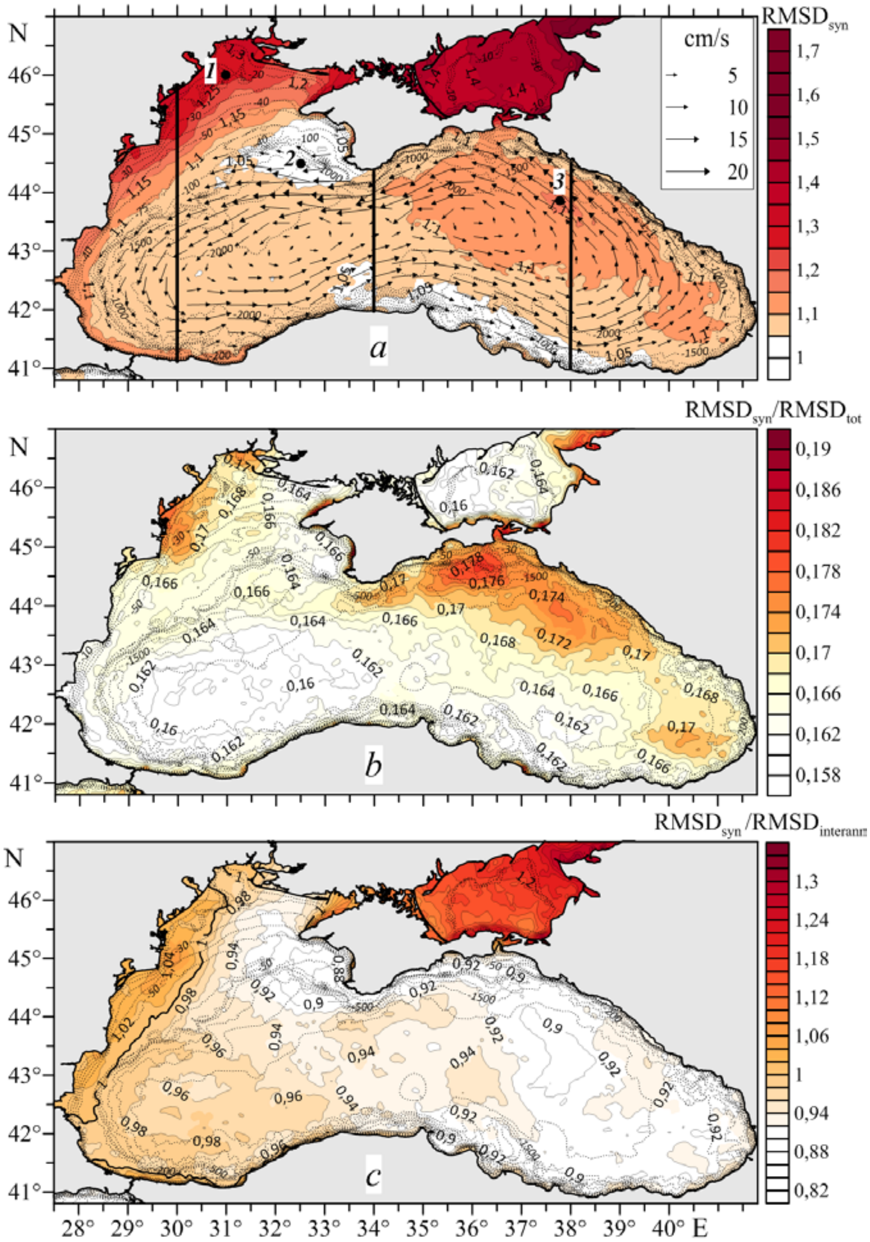
The interannual variations of the SST synoptic variability were analyzed at each grid node in time series, containing 37 values of SST $RMSD_{syn}$ averaged for each year for 1982–2018period. In addition, to assess the relationship between the SST synoptic variations and large-scale atmospheric modes, cross-correlation functions (at a 95% level of statistical significance) were calculated between time series consisting of 444 SST $RMSD_{syn}$ and the indices of the North Atlantic (NAO) and East Atlantic (EAO) oscillations and the East Atlantic – Western Russia (EA/WR) fluctuation (https://www.cpc.ncep.noaa. gov/data/teledoc/telecontents.shtml).

To interpret the regional features of the $RMSD_{syn}$ spatial distributions, the structure of the large-scale geostrophic water circulation relative to the reference surface of 300 dbar was analyzed according to the climatic array data of thermohaline fields created at Marine Hydrophysical Institute [23].

Results of the research

Spatial distributions of the mean long-term SST $RMSD_{syn}$ (Fig. 1a) showed that their maximum values (~ 1.25–1.35 °C) are observed above sea depths of less than 20–30 m in the coastal part of the northwestern shelf from the Dnieper-Bug estuary to the Danube delta and in the Karkinit Bay and in the Kerch Strait. The synoptic variability level increase of ($RMSD_{syn}$ ~ 1.1–1.25 °C) is also observed along the entire western shelf and in the pre-Bosporus area, almost up to Cape Olyudzhe above the sea depths less than 75 m. In the deep-sea part, high $RMSD_{syn}$ values (up to 1–1.2 °C) can be traced in the areas of the Eastern cyclonic gyre (ECG) and the Batumi anticyclone, which is more clearly manifested according to actual surveys, satellite altimetry and model calculations [4, 12, 15, 24]. The minimum $RMSD_{syn}$ values (below 1 °C) are observed in the coastal strip along the Anatolian coast between Cape Olyudge and Cape Fener, as well as in the region of the minimum seasonal variation of SST [5, 25] to the west of the Crimean coast.

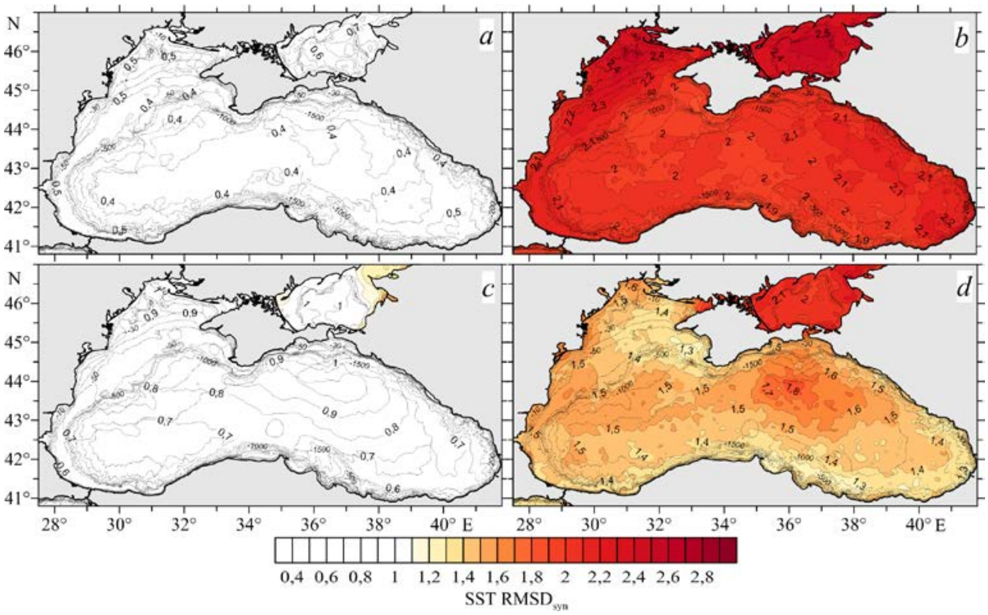
The $RMSD_{syn}/RMSD_{tot}$ ratio values throughout the entire water area vary in a relatively narrow range of 0.158–0.182 (Fig. 1, *b*). The greatest contribution of synoptic variability to the total dispersion of the SST field ($RMSD_{syn}/RMSD_{tot}$ = = 0.176–0.182) is observed in the Kerch Strait and above the dump depths south of the Kerch Peninsula. An increase in the $RMSD_{syn}/RMSD_{tot}$ values (above 0.17) is also observed on the northwestern shelf between the Dnieper-Bug estuary and the Danube delta, in the northeastern part of the sea and in the Batumi anticyclone area. The minimal contribution of synoptic variability to the total dispersion of the SST field ($RMSD_{syn}/RMSD_{tot}$ below 0.16) was found in the Western cyclonic gyre (WCG), where an increase in the seasonal variability level was noted [5, 25].



F i g. 1. Distribution of the long-term average values of SST $RMSD_{syn}$ (*a*), $RMSD_{syn}/RMSD_{tot}$ (*b*), $RMSD_{syn}/RMSD_{interann}$ (*c*). The arrows indicate the vectors of the annual average geostrophic currents on the surface; the dotted lines are isobaths; points *1*, *2* and *3* are the grid nodes for which the graphs of intra-annual distributions of the SST $RMSD_{syn}$ values are represented on Fig. 3, *d*

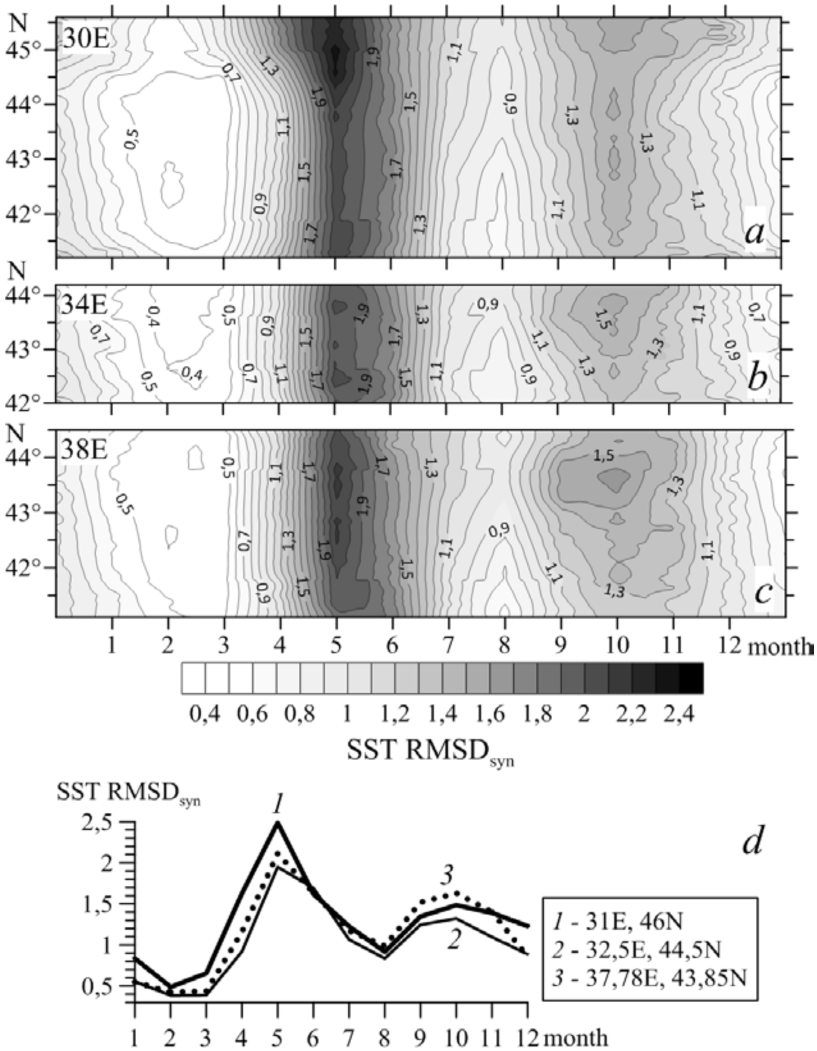
In most of the sea area, the synoptic variability level is lower or comparable to interannual one and the $RMSD_{syn}/RMSD_{interann}$ values vary within 0.88–1

(Fig. 1, *c*). The SST synoptic variability exceeds the interannual ($RMSD_{syn}/RMSD_{interann}>1$) in the coastal regions of the western sea part, where the maximum $RMSD_{syn}$ values are found, in the Karkinit Bay, in the Dnieper-Bug Estuary, on the western shelf from the Dniester Estuary to the Burgas Bay and on the Bosporus shelf. In the eastern sea part, the SST synoptic variations are lower than interannual ones and exceed them only in the Kerch Strait. Despite the high level of synoptic variability in the ECG and Batumi anticyclone zones, $RMSD_{syn}/RMSD_{interann}$ is below 0.92, which is associated with a high level of interannual SST variability in these areas [5].



F i g. 2. Spatial distribution of the SST $RMSD_{syn}$ climatic values in February (*a*), May (*b*), August (*c*), October (*d*)

From an analysis of the spatial distributions of $RMSD_{syn}$ values for each month and their intra-annual cycle along individual meridians, it follows that the minimum SST synoptic variability is observed in February – March (Fig. 2, *a*; 3, *a* – *c*), during $RMSD_{syn}$ values in the entire water area do not exceed 0.3–0.4 °C. In April, when intense heating begins, a sharp increase in the synoptic variability level occurs, reaching maximum in May (Fig. 2, *b*; 3, *a* – *c*). This month, the SST $RMSD_{syn}$ values in the water area vary within 1.8–2.6 °C. In June, the surface water heating rate is maximum [25], while the level of synoptic variability sharply decreases. In July, the heating rate slows down, and the level of synoptic variability continues to decrease and reaches minimum in August (Fig. 2, *c*; 3, *a* – *c*), when the SST is maximum in the entire water area. This month, the $RMSD_{syn}$ values do not exceed 0.7–0.9 °C. In September, with the beginning of autumn water cooling, the synoptic variability level begins to increase, and in October its second maximum is observed with $RMSD_{syn}$ values of ~ 1.2–1.9 °C (Fig. 2, *d*). In November, when the maximum rate of autumn-winter cooling of surface waters is observed, the SST synoptic variability level decreases again and continues to decrease gradually until February – March (Fig. 3, *a* – *c*).



F i g. 3. Intra-annual cycle of the SST $RMSD_{syn}$ climatic values along 30E (*a*), 34E (*b*), 38E (*c*), and in separate grid nodes *1*, *2*, *3* (*d*)

The nature of the seasonal signal of the SST synoptic variability level does not change in space even in areas with extreme values of the mean long-term $RMSD_{syn}$. Fig. 3, *d* shows that the seasonal signal $RMSD_{syn}$ is at point 1 (in the region of the maximum average long-term $RMSD_{syn}$ values on the north-western shelf), at point 2 (west of Crimea, where the minimum $RMSD_{syn}$ is traced) and at point 3 (in the north-eastern peripheral ECG, where increased $RMSD_{syn}$ values are observed) is the same.

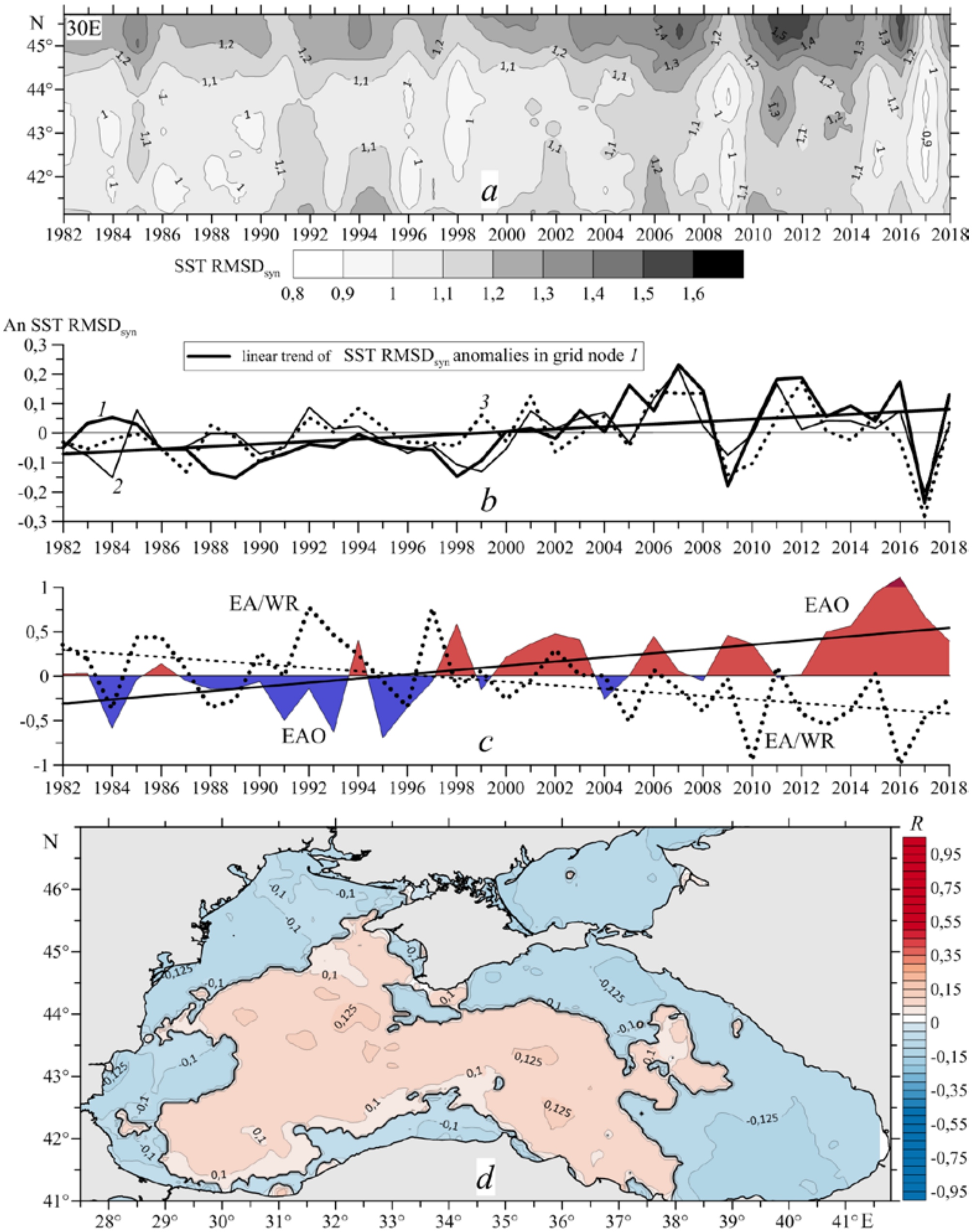
Despite noticeable intra-annual changes in of the SST synoptic variability level, the main spatial features revealed for the distribution of long-term average values of $RMSD_{syn}$, are observed in all months. The maximum $RMSD_{syn}$ values are traced throughout the year on the northwestern shelf (Fig. 3, *a*). Increased $RMSD_{syn}$ values are observed on the Bosporus shelf (Fig. 3, *a*) and in the eastern sea part on the northern ECG periphery (Fig. 3, *b*). A decrease of $RMSD_{syn}$ values is observed over the coastal part of the Anatolian coast (Fig. 3, *c*).

Analysis of interannual SST $RMSD_{syn}$ variations for 1982–2018 revealed noticeable changes in the SST synoptic variability level of the Black Sea from year to year. The values of interannual anomalies of the average annual $RMSD_{syn}$ (An $RMSD_{syn}$) throughout the entire water area vary in the range −0.3 ... 0.3 °C. Moreover, the spatial distribution features revealed for the long-term average $RMSD_{syn}$ values (see Fig. 1, *a*) are manifested throughout all years: the maximum average annual $RMSD_{syn}$ values are always traced on the northwestern shelf (Fig. 4, *a*), and the increased $RMSD_{syn}$ values – in areas of the Bosporus shelf and on the northern ECG periphery, lowered in the coastal part of the Anatolian coast and off the western coast of Crimea.

In contrast to the climatic intra-annual variation of the SST $RMSD_{syn}$ values, the nature of which does not change throughout the sea, the distributions of interannual SST $RMSD_{syn}$ anomalies in different regions of the sea differ (Fig. 4, *b*). So, on the northwestern shelf (point 1), the average annual SST $RMSD_{syn}$ values in 1982–2002 were predominantly lower or close to their mean long-term value, while the largest negative anomalies of $RMSD_{syn}$ (up to −0.15 °C) were noted in 1989 and 1998. To the west of Crimea (point 2) and on the northeastern ECG periphery (point 3) in these years, the $RMSD_{syn}$ values were close to the climatic norm.

Since 2003, in the entire water area, the average annual SST $RMSD_{syn}$ has been predominantly higher than the long-term average, except for 2009 and 2017. The maximum positive anomalies of $RMSD_{syn}$ were observed on the northwestern shelf (point 1), in 2007, 2011, 2012 and 2016 they reached 0.25, 0.18, 0.2 and 0.17 °C, respectively (Fig. 4, *b*). In the time series of the interannual $RMSD_{syn}$ anomalies at point 1 and the average annual values of the EAO index, a significant positive linear trend is traced, and the EA/WR index is a negative trend (Fig. 4, *b*, 4, *c*). At the same time, in the distributions of interannual anomalies of the average annual $RMSD_{syn}$ and the EAO, NAO and EA/WR indices, the general periodicities are not explicitly manifested (Fig. 4, *b*, 4, *c*). Thus, high negative $RMSD_{syn}$ anomalies (−0.2 ... −0.3 °C) in 2009 were observed with a positive EAO phase, a negative NAO phase and an EA/WR index close to zero, whereas in 2017 – with a positive EAO phase, a negative EA/WR phase and a close to zero NAO index value (Fig. 4, *b*, 4, *c*).

The distributions of the *R* maxima of the cross-correlation functions calculated at each grid node between the time series of the monthly average values of $RMSD_{syn}$ and the EAO, NAO and EA/WR indices for 1982–2018 showed that there is no significant relationship between these parameters in the entire sea area. The highest *R* maxima values were revealed for cross-correlation functions between $RMSD_{syn}$ and the EA/WR index (Fig. 4, *d*), but even they do not exceed 0.125 in absolute value. Note that, for the interannual SST variability itself, on the contrary, a significant correlation was found with the NAO index [5, 7].



F i g. 4. Inter-annual time series of the annual average values of the SST $RMSD_{syn}$ along 30°E (*a*), interannual anomalies of the SST $RMSD_{syn}$ at the grid nodes *1*, *2* and *3* (*b*), the inter-annual time series of annual average values of the EAO and EA/WR indices and their linear trends (*c*), spatial distribution of the maximum *R* of the cross-correlation functions between the values of the SST $RMSD_{syn}$ and EA/WR index (*d*)

Conclusion

Based on the satellite data analysis for 1982–2018, it is shown that the maximum mean long-term synoptic SST variability ($RMSD_{syn}$ ~ 1.25–1.35 °C) is observed above sea depths of less than 20–30 m in the coastal part of the northwestern shelf from the Dnieper-Bug estuary to the Danube delta, in the Karkinit Bay and in the Kerch Strait. The synoptic variability level increase ($RMSD_{syn}$ ~ 1.1–1.25 °C) is observed along the entire western shelf, in the pre-Bosporus region above the sea depths of less than 75 m and in the areas of the Eastern cyclonic circulation and the Batumi anticyclone. The minimum values of $RMSD_{syn}$ (below 1 °C) are observed in a narrow coastal strip along the Anatolian coast and west of Crimea coast.

The greatest contribution of synoptic variability to the total dispersion of the SST field is observed in the Kerch Strait and south of the Kerch Peninsula, and the minimal one – in the southwestern sea part in the WCG area. In most part of the sea, the average annual synoptic SST variability is lower or comparable with the interannual variability level. The synoptic SST variations exceed the interannual ones only in the Kerch Strait, on the northwestern and pre-Bosphorus shelves.

In the intra-annual cycle, the synoptic SST variability level is characterized by a semi-annual periodicity due to large-scale processes of cooling and heating of the waters. Maximums are observed in May and October, a month before the onset of maximums of the rate of heating and cooling of surface waters, and minimums are observed in February – March and August, during periods of maximum cooling and heating.

Throughout the entire sea area, the values of interannual anomalies of the average annual SST $RMSD_{syn}$ vary in the range of −0.3 ... 0.3 °C. In all years, the maximum average annual SST $RMSD_{syn}$ values are traced on the north-western shelf, the minimum ones – on the coastal part of the Anatolian coast and off the western coast of Crimea.

In the distributions of interannual anomalies of the mean annual $RMSD_{syn}$ and atmospheric circulation EAO, NAO and EA/WR indices, common periodicities are not clearly observed. Only the presence of a positive linear trend in the time series of interannual anomalies of the mean annual $RMSD_{syn}$ values on the northwestern shelf was noted, while the interannual distributions of the average annual values of the EAO index also showed a positive linear trend, and the EA/WR index showed a negative trend. No significant correlation was found between the time series of the values of the $RMSD_{syn}$ and the EAO, NAO and EA/WR indices.

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