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Reconstructing the Black Sea Hydrophysical Fields Including Assimilation of the Sea Surface Temperature, and the Temperature and Salinity Pseudo-Measurements in the Model

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Purpose. The investigation is aimed at increasing accuracy of the temperature field reconstruction in the Black Sea upper layer. For this purpose, satellite observations of the sea surface temperature and the three-dimensional fields of temperature (in the 50–500 m layer) and salinity (in the 2.5–500 m layer) pseudo-measurements, previously calculated by the altimetry and the *Argo* floats data, were jointly assimilated in the Marine Hydrophysical Institute model.
Methods and Results. Assimilation of the sea surface temperature satellite observations is the most effective instrument in case the discrepancies between the sea surface and the model temperatures are extrapolated over the upper mixed layer depth up to its lower boundary. Having been analyzed, the temperature profiles resulted from the forecast calculation for 2012 and from the Argo float measurements made it possible to obtain a simple criterion (bound to the model grid) for determining the upper mixed layer depth, namely the horizon on which the temperature gradient was less or equal to ≤ 0.017 °C/m. Within the upper mixed layer depth, the nudging procedure of satellite temperature measurements with the selected relaxation factor and the measurement errors taken into account was used in the heat transfer equation. The temperature and salinity pseudo-measurements were assimilated in the model by the previously proposed adaptive statistics method. To test the results of the sea surface temperature assimilation, the Black Sea hydrophysical fields were reanalyzed for 2012. The winter-spring period (January – April, December) is characterized by the high upper mixed layer depths, well reproducible by the Pacanowski – Philander parameterization, and also by the low values (as compared to the measured ones) of the basin-averaged monthly mean square deviations of the simulated temperature fields. The increased mean square deviations in July – September are explained by absence of the upper mixed layer in the temperature profiles measured by the *Argo* floats that is not reproduced by the Pacanowski – Philander parameterization.
Conclusions. The algorithm for assimilating the sea surface temperature together with the profiles of the temperature and salinity pseudo-measurements reconstructed from the altimetry data was realized. Application of the upper mixed layer depths estimated by the temperature vertical profiles made it possible to correct effectively the model temperature by the satellite-derived sea surface temperature, especially for a winter-spring period. It permitted to reconstruct the temperature fields in the sea upper layer for 2012 with acceptable accuracy.

Keywords: Black Sea, satellite sea surface temperature, depth of the upper mixed layer, altimetry, assimilation.

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Introduction

Earlier, in [1, 2], an original technique for reconstructing temperature and salinity three-dimensional fields of the Black Sea from limited measurement data at hydrological stations and *Argo* buoys using altimetry was proposed. The developed methodology is based on the idea of the presence of waters' basic stratification of the Black Sea deep-water part, depending only on the vertical coordinate. At the same time, it was shown in [2] that on synoptic scales the real stratification observed at each point is formed mainly by adiabatic displacements of isopycnic, as well as isothermal and isohaline surfaces at depths from 50–100 to 1100–1200 m. Moreover, in [2], it was revealed that the distribution of the displacement amplitudes of isothermal and isohaline surfaces over the depth is one-parameter with high accuracy and, therefore, is determined by the deviation of the sea level from its mean value. It is also shown in [2] that both the basic stratification of waters of the Black Sea deep-water part and the one-parameter dependence of the isothermal and isohaline surfaces displacement on the level deviation at a given point vary from season to season and from year to year. Therefore, in [2], an array of monthly average distributions of the basic stratification and displacements of isothermal and isohaline surfaces was formed on a regular grid. As a result, using *AVISO* distribution of the Black Sea level anomalies, the daily profiles of temperature and salinity were reconstructed at the nodes of MHI model regular grid [3] at 63–500 m layer horizons for 1993–2014 in the deep-water part of the sea, limited by 500 m isobath [4]. These profiles are hereinafter referred to as pseudo-measurements, since they are not the result of measurements but are obtained through a combination of satellite altimetry and limited temperature and salinity measurements carried out by *Argo* buoys [4]. An essential fact is that the fields of temperature and salinity pseudo-measurements characterize the main synoptic processes.

Assimilation of the obtained data arrays in the Black Sea water circulation model during the retrospective analysis for 1993–2014 provided the reconstruction of hydrophysical fields throughout the entire depth for the entire sea basin. In the main pycnocline, a satisfactory root-mean-square deviation (RMSD) of the reconstructed temperature and salinity fields from those measured at hydrological stations and *Argo* buoys was obtained. However, in 0–50 m upper layer, the RMSD of both temperature and salinity turned out to be significant [4].

The use of the iterative algorithm proposed in [5] made it possible to reconstruct, with satisfactory accuracy, the daily pseudo-measurements of temperature in the layer from 50 to 500 m and salinity in the layer from the sea surface to 500 m at the grid nodes of the model.

The reconstructed fields of salinity pseudo-measurements from the sea surface to 500 m depth and temperature in 50–500 m layer were assimilated in the water circulation model in the reanalysis for 2012. Analysis of the calculations showed that the salinity RMSD decreased to quite acceptable values. Temperature field RMSD also slightly decreased but its values in 0–40 m layer turned out to be unsatisfactory [5].

In this work we performed a joint assimilation in the model of three-dimensional fields of pseudo-measurements of sea water temperature in 50–500 m layer and salinity in 2.5–500 m layer by the method of adaptive statistics and sea surface temperature (SST) from satellite observations by means of model temperature relaxation to the one observed within the upper mixed layer (UML). The calculation results provided more accurate reconstruction of the sea water temperature fields in the Black Sea upper layer for 2012.

Algorithm for SST assimilation in the model, selection of parameters and validation

Assimilation of satellite SST data in the model is necessary to improve the accuracy of the Black Sea hydrophysical fields reconstructed in the reanalysis, especially in its near-surface and upper layers of 0–50 m, in which time variability of heat fluxes on the sea surface is significant and the imperfection of turbulent exchange models within UML also plays its role. Assimilation of SST satellite observations is most effective if the discrepancies between the observed and calculated temperatures are extrapolated in depth down to the UML lower boundary. Therefore, when constructing an algorithm, it is necessary to correctly determine the UML depth.

Method of UML depth determination

In order to develop a method for determining the UML depth, the temperature profiles presented earlier in [4–6] for 2012 and obtained from measurements of *Argo* floats this year [7, 8], were preliminary analyzed according to the data of numerical calculations. Taking into account the seasonal peculiarities of temperature profiles formation in 0–100 m upper sea layer (atmospheric thermal conditions, the presence of a cold intermediate layer (CIL) and its renewal in winter and formation in spring), we obtained a fairly strict criterion for determining the UML depth of linked to the model grid – the magnitude of the vertical temperature gradient. Thus, the UML depth at each model grid point is defined as a horizon z_{k+1} on which the gradient is

$$\text{abc}\{[T(z_{k+1}) - T(z_k)]/(z_{k+1} - z_k)\} \leq 0.017\ \text{°C/m}\,. \tag{1}$$

The quality of the proposed criterion was assessed by comparison with the results of work [9]. In this work, the climatic monthly mean fields of the UML depths of the Euxinus cascade seas (Azov, Black, Marmara and Aegean) were studied. These depths were obtained from the available field data of temperature and salinity measurements [10–12]. The UML depth was determined using several algorithms. The first of them was used to calculate the difference

$$\Delta\sigma_t = \sigma_t(T + \Delta T, S, P) - \sigma_t(T, S, P), \tag{2}$$

calculated at a specific node of the horizontal grid by the data on temperature T and salinity S at 3 m horizon. In this case, the pressure P = 0, and the increment ΔT = 0.8 °C. For σ_t calculation, in [9] the standard UNESCO equation [13, p. 629] was used. The UML depth was identified with the horizon z_{k-1}, below which the inequality

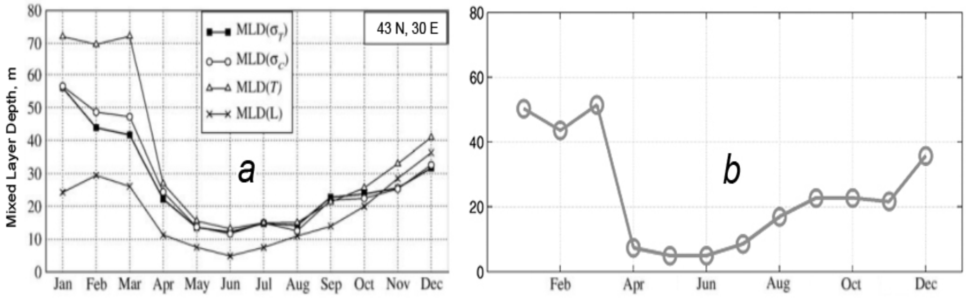
$$\text{abc}[\sigma_t(z_1) - \sigma_t(z_k)] \leq \Delta\sigma_t \tag{3}$$

is violated. In relation (3) $\sigma_t(z_1)$ denotes a conditional density $\sigma_t(T,S,P)$ at the basic horizon of 3 m, and $\sigma_t(z_k)$, k = 2, 3, … – relative density at the horizons lying below.

According to the second algorithm, which the authors of [9] abbreviated as *MLD*(*T*), only temperature profiles were analyzed. In this case, in a relationship similar to (3), the conditional density was replaced by temperature and a fixed value ΔT = 0.8 °C was set on the right side of the inequality. Thus, the UML depth was identified with the depth of the isothermal layer, in which the temperature deviates from the one at 3 m horizon by no more than ΔT = 0.8 °C.

For comparison, in [9] the climatic maps of UML depths, estimated by relation (3), in which the right side was equal to 0.125 kg/m^3, were constructed. This value was also used in [14, 15] to determine the depth of the UML in the water area of the Pacific Ocean northern part. Some of the UML depth maps in [9] were constructed using an algorithm borrowed from [16]. According to this algorithm, the UML depth is determined by searching for the first extremum of the temperature profile curve. Comparison of the results of the UML depth calculating using different algorithms for the winter season (January) showed that the greatest depth values were obtained using *MLD*(*T*) algorithm. The maximum depth differences calculated by *MLD*(*T*) algorithm and by formulas (2), (3) reach ~ 35 m values. In the summer season (July), the UML depths differ insignificantly. Therefore, further we used for comparisons the results of the UML depth calculations obtained in [9] using *MLD*(*T*) algorithm.

Seasonal variability of the climatic mean monthly UML depth for 1913–2004, estimated in [9] using *MLD*(*T*) algorithm at the point of the Black Sea with coordinates 43° N, 30° E were compared with the variability of the mean monthly UML depth at the same point, calculated using criterion (1) based on predictive (i.e. without assimilation of observations but with real atmospheric forcing) calculation using the model for 1993–2012 (Fig. 1). Note that in this calculation the coefficients of turbulent diffusion of heat and salt along the vertical were set using Pacanowski – Philander formula, adapted for the Black Sea. The same parameterization was used in further calculations in this work due to its cost-effectiveness in comparison with more advanced models of turbulence in the UML. From Fig. 1 it can be seen that the corresponding variability curves have qualitatively the same time variation. The curves in Fig. 1 are close to each other in August – October and December. However, according to [9], the climatic depths of the UML are noticeably greater in January – March and November. A possible cause for this may be an overestimated threshold value of temperature difference ΔT = 0.8 °C. The application of *MLD*(*T*) algorithm to the analysis of the Black Sea CIL temperature profiles, calculated in numerical experiments, showed that at such a threshold value the calculated UML in winter period sometimes includes the entire CIL, which affects the monthly average value of the UML depth. The divergence of curves in April – July is most likely due to the use of Pacanowski –Philander vertical mixing parameterization, which underestimates the UML depths in this time interval.



F i g. 1. Seasonal variability of the mixed layer depth: *a* – based on the data from [9], *b* – based on prognostic calculation for 1993–2012

Algorithm of SST assimilation in the model

When carrying out calculations in this work, MHI model was used [3]: the horizontal resolution in this version of the model is 5 × 5 km, 38 vertical horizons (2.5; 5; 10;…; 30; 40; 50; 63; 75; 88; 100; 113; 125; 150; 175; 200; 250; 300; 400; ...; 2100 m). As noted above, the vertical mixing was parametrized using the Pacanowski – Philander approximation [17] with selected parameter values for the Black Sea. The same approximation was applied in [18] for the diagnosis of climatic seasonal circulation in the sea. The Pacanowski – Philander approximation is also used in [19], in which the hydrophysical fields of the Black, Azov and Marmara Seas are calculated using the *INMOM* (*Institute of Numerical Mathematics Ocean Model*) version of σ-model of marine circulation with 1 km horizontal resolution and validated using the data from *Argo* buoys.

For testing the results of SST assimilation in the model, as well as to select some parameters, we performed a retrospective analysis of the sea hydrophysical fields for 2012. The fields of atmospheric forcing parameters were borrowed from *ERA-Interim* reanalysis data [20]. The choice of this period is due to several reasons. The assimilation of three-dimensional fields of the sea water temperature (salinity) pseudo-measurements according to altimetry data and limited measurements of temperature profiles by *Argo* buoys for 2012 was carried out earlier [5] without involving SST. According to the data of [21], this year is characterized by cold winter thermal conditions of the atmosphere and a strong CIL renewal. Therefore, the results of calculations performed in [5] are used below to validate the reconstructed hydrophysical parameters with SST assimilation in the model.

The sea surface temperature for the implementation of the algorithm was taken from the daily maps of *SST*, *PODAAC (NASA)* [22]. It was interpolated to the model grid and assimilated through relaxation of the model temperature to the observed one. For this, within the UML depth, the differences between the temperature observed on the sea surface and the model one were calculated. With the selected relaxation coefficient, they were taken into account at each time step at the model grid nodes in the equation of heat transfer by sources of the form

$$Q_{Ti,j,k} = \frac{1}{\mathrm{REL1}(1+\eta^2)}(T_{i,j}^{SST} - T_{i,j,k}^{MOD}), \tag{4}$$

where η^2 is a measure of SST measurement error equal to the ratio of the square of temperature measurement error (0.25 ºC^2) to the dispersion of natural variability $T_{i,j}^{SST}$ is a satellite SST; $T_{i,j,k}^{MOD}$ is a model temperature; *i* [1, 238] is a number of nodes along *x*-axis, *j* [1, 132] – along *y*-axis, *k* [1, *n*] – along *z*-axis; *n* is a number of horizon determining the UML depth. Simultaneously, taking into account the sources (4), the model assimilated previously prepared pseudo-measurements of temperature (in 50–500 m layer) and salinity (in a layer from the surface down to 500 m) by including the sources of the form

$$Q_{\mathrm{Ti,j,k}} = \frac{\sigma^2_{\mathrm{Ti,j,k}}}{\mathrm{REL2}\left[\sigma^2_{\mathrm{Ti,j,k}}+\gamma^{\mathrm{T}}_{\mathrm{k}}\sigma^2_{\mathrm{erT}}\right]}\left[\mathrm{T}^{\mathrm{OBS}}_{\mathrm{i,j,k}}-\mathrm{T}^{\mathrm{MOD}}_{\mathrm{i,j,k}}\right], \quad (5)$$

$$Q_{\mathrm{Si,j,k}} = \frac{\sigma^2_{\mathrm{Si,j,k}}}{\mathrm{REL2}\left[\sigma^2_{\mathrm{Si,j,k}}+\gamma^{\mathrm{S}}_{\mathrm{k}}\sigma^2_{\mathrm{erS}}\right]}\left[\mathrm{S}^{\mathrm{OBS}}_{\mathrm{i,j,k}}-\mathrm{S}^{\mathrm{MOD}}_{\mathrm{i,j,k}}\right]. \quad (6)$$

Here $\sigma^2_{Ti,j,k}$, $\sigma^2_{Si,j,k}$ are the dispersions of the temperature and salinity reanalysis errors, respectively, calculated using the adaptive statistics method [6]; $\gamma_k^T\sigma^2_{\mathrm{er}T}$, $\gamma_k^S\sigma^2_{\mathrm{er}S}$ are empirically selected constants ($\gamma_k^T, \gamma_k^S \le 0{,}015$), multiplied by the monthly average variances of errors in reconstructing temperature and salinity pseudo-measurements, respectively [5]; $T_{i,j,k}^{OBS}$, $S_{i,j,k}^{OBS}$ are temperature and salinity pseudo-measurements; the indices *i*, *j* vary in the deep sea area bounded by 500 m isobath, and the index *k* takes the values *k* [9, 22] and *k* [1, 22] in equations (5) and (6), respectively. The relaxation parameter REL2, equal to 12 h, was selected in [6].

Selection of REL1 parameter and validation of the calculation results

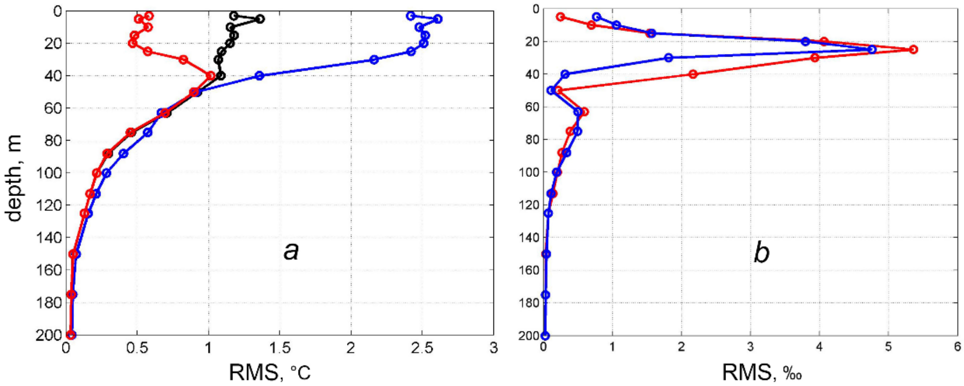
In order to select the relaxation coefficient REL1 in a source of the form (4), numerical experiments on the reanalysis of the sea hydrophysical fields for 2012 with the SST assimilation in the model at REL1 = 1, 5, 10 days and pseudo-measurements of temperature and salinity with the value REL2 = 12 h [6] were performed. It can be seen from the table that at most of horizons of 2.5–100 m layer, the temperature RMS estimated from the calculation data at REL1 = 10 days turned out to be higher than at REL1 = 1 and 5 days. Therefore, further we will focus on calculations with these two values of REL1 parameter.

Further we consider the profiles of temperature and natural variability RMS deviation averaged over the basin for each month (the square root of variance of the measured temperature fields). Their analysis shows (Fig. 2, *a*) that according to the RMS deviation values, the winter-spring period (January – April, December) is distinguished, when the maximum RMS values in the upper sea layer are relatively small and vary from 0.42 °C in January to 0.95 °C in April and 1.83 °C in December at 40, 50, and 40 m depths, respectively, with REL1 = 5 days. At REL1 = 1, the RMS values differ insignificantly. At this time of the year, the UML depth is maximum and is well reproduced by Pacanowski – Philander parameterization. In May – October, the accuracy of calculating the temperature in the upper sea layer with SST assimilation significantly increases compared to the calculation when SST was not assimilated [5]. Nevertheless, the error in calculating the temperature in the surface layer remains quite high. At REL1 = 5 days, the maximum RMS deviation values for May, June and July increase: 1.62 °C (at 20 m depth), 3.0 °C (at 10 m depth), and 3.43 °C (at 10 m depth). The highest RMS values were obtained in summer in August (5.27 °C at 15 m depth) and in autumn in September (6.1 °C at 20 m depth). For example, in Fig. 2, *b* the RMS deviation profile for October is given.

Root mean square deviations of the model-reconstructed temperature fields from the data measured at the horizons in 2012

Horizon, m	RMS deviations, °C		
	REL1		
	1 day	5 days	10 days
2.5	0.503	1.113	1.409
5.0	0.556	1.008	1.398
10.0	2.141	1.927	2.141
15.0	3.969	3.429	3.461
20.0	5.018	4.438	4.337
25.0	4.447	4.021	3.905
30.0	3.137	2.902	2.793
40.0	1.602	1.481	1.465
50.0	0.659	0.663	0.682
63.0	0.647	0.655	0.679
75.0	0.499	0.505	0.517
88.0	0.345	0.342	0.344
100.0	0.268	0.268	0.269

The deviation in May – August of the temperature monthly mean profiles reconstructed in the reanalysis at REL1 = 5 days from the monthly mean profiles of the observed temperature in the layer of the seasonal thermocline (horizons 10, 15, 20, 25, 30 and 40 m) is less than the model profile deviation at REL1 = 1 day from the observed profile. The accuracy of reconstructing the temperature fields at these horizons with REL1 = 5 days is higher, as evidenced by the table. At the same time, the accuracy of SST reconstruction at REL1 = 1 day is higher than at REL1 = 5 days.

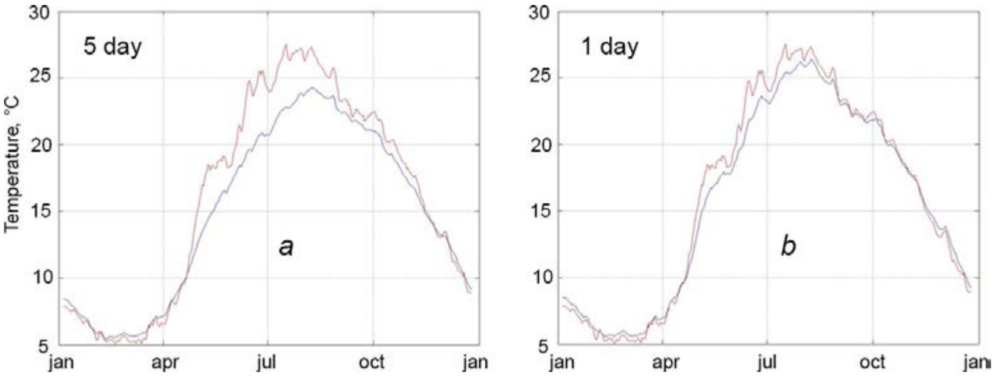


F i g. 2. Root mean square deviations of temperature (°C) calculated using the reanalysis data for 2012: *a* – basin-averaged profiles for January – April and December; *b* – basin-averaged profiles for October (red curve shows mean square deviations of temperature based on the reanalysis data including sea surface temperature assimilation, blue curve – natural variability of the measured temperature)

Increased values of RMS deviation near the seasonal thermocline in the spring-summer season are quite expected: with large vertical gradients, small errors in determining the thermocline depth lead to significant errors in determining the temperature even with the assimilation of available observations. This problem is especially significant in the Black Sea, where the summer thermocline is very shallow and sharpened. However, in July – September in the presented calculation, the RMS deviation values were overestimated too. The cause is that the Pacanowski – Philander parameterization, which has shown itself to be quite good when calculating mean UML depth for 1993–2012 (Fig. 1), turned out to be insufficiently optimized for the calculation of 2012. In July – September 2012, the UML in the temperature profiles measured by *Argo* buoys was absent in the overwhelming majority of cases, but the Pacanowski – Philander parameterization does not reproduce this absence. Specifying an incorrect UML depth during the SST assimilation leads to distortion of the model temperature profile in the UML and seasonal thermocline. A different type of the model temperature profile curvature in comparison with the observed one also explains the improvement in the accuracy of temperature calculations in comparison with observations in 10–40 m layer at REL1 = 5 days. In order to improve the accuracy of water temperature calculations in the upper layer with assimilation of SST observations when using the Pacanowski – Philander parameterization, it is necessary to clarify the values of the constants, taking into account which the vertical diffusion coefficients are calculated. In this case, a possible solution is to set the seasonal variation of the determining coefficients in the Pacanowski – Philander parameterization, which is a separate rather complicated problem. However, even with such a solution, it is unlikely that it will be possible to avoid an abnormal increase in RMS deviation in particular years that differ from climatic fields. Another alternative is the use of less economic turbulence models of Mellor – Yamada type [23, 24].

Results and discussion

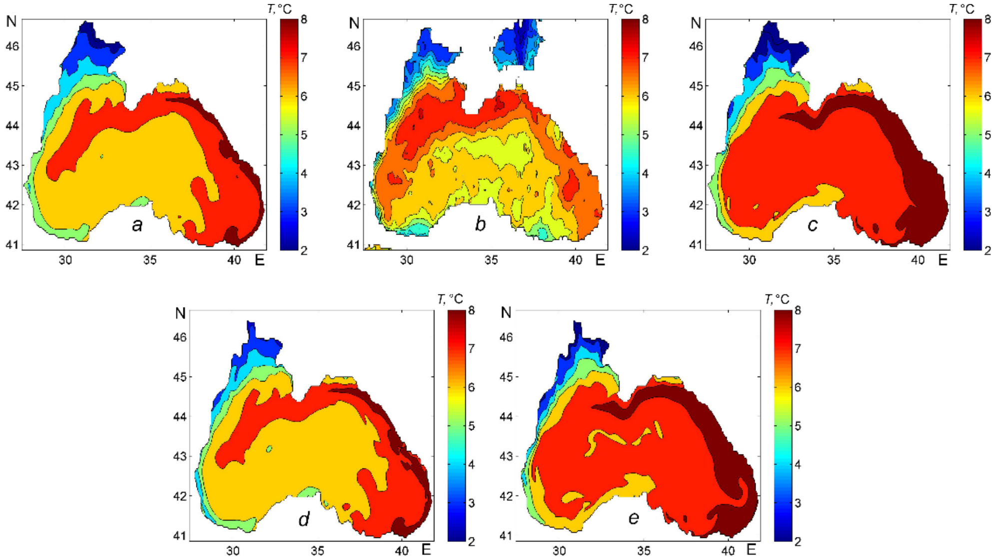
Now we are to consider the seasonal variability of the satellite temperature averaged over the sea surface and the model temperature reconstructed by means of relaxation to the observed one (Fig. 3). In Fig. 3, *a* it can be seen that at REL1 = 5 days both curves slightly differ from each other in January – April and from mid-November to December inclusive. Significant downward deviations of the model-reconstructed surface temperature from the satellite temperature are observed in the period from May to August inclusive. For finding out the cause, we analyzed the spatial distributions of the surface temperature, calculated in the version of calculations without SST assimilation in the model, in the indicated months of the year. The surface temperature in this calculation turned out to be underestimated in comparison with the satellite temperature. Obviously, the cause lies in the temporal variability of heat fluxes used in the boundary condition for the sea surface temperature.



F i g. 3. Seasonal variability of the average over the sea surface temperature: *a* – relaxation parameter REL1 = 5 days; *b* – relaxation parameter REL1 = 1 day (red curve – based on satellite data, blue curve – based on model data)

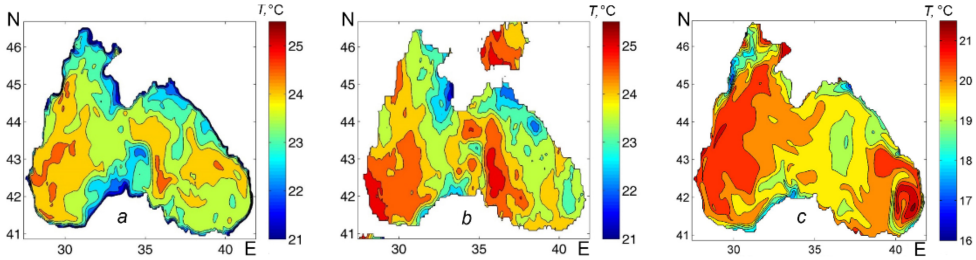
The model temperature with REL1 = 1 day approaches the satellite one (Fig. 3, *b*). In this case, as noted above, the RMS deviation values of the model temperature in the seasonal thermocline (at 10–40 m horizons) increase in comparison with the RMS deviation values obtained from the data of the variant of calculations with REL1 = 5 days. Since 2012 is characterized by a strong degree of CIL renewal [21], which will be discussed below, further we will analyze the calculation results with REL1 = 5 days.

The spatial structure of the reconstructed surface temperature fields with SST assimilation in the model was compared with the data/results of satellite observations, as well as with the surface temperature calculated without SST assimilation. In the latter case, only three-dimensional fields of temperature pseudo-measurements in 50–500 m layer and salinity in 2.5–500 m layer were assimilated. According to Fig. 4, *a* and Fig. 4, *b*, the distributions and configurations of the structures of increased and decreased winter temperatures calculated with SST assimilation are close to the temperature obtained from satellite measurements. Low temperatures are observed in the northwestern shallow sea area and along the western and southern coasts, including the sea area eastwards of Sakarya River outlet. The increased temperature is typical for the vast southeastern water area of the sea and the area enveloping the eastern and southern coasts of the Crimean Peninsula and extending westwards and southwestwards. In the central deep-water area and along the Caucasian coast the temperature is somewhat overestimated (Fig. 4, *a* and Fig. 3, *a*). At the same time, the surface temperature, reconstructed without SST assimilation in the model (Fig. 4, *c*) turned out to be overestimated almost over the entire sea area, especially in the sea strip adjacent to the Caucasian coast and the eastern and southern regions of the Crimea Peninsula. Reduced temperature, as in Fig. 4, *a*, *b*, is observed in the northwestern shallow area and in the water area extending from the Crimean western coast to the southwest and south up to Sinop. Temperature fields in Fig. 4, *a*, *d* are almost identical, which indicates a mixed water layer of 2.5–20 m thickness.

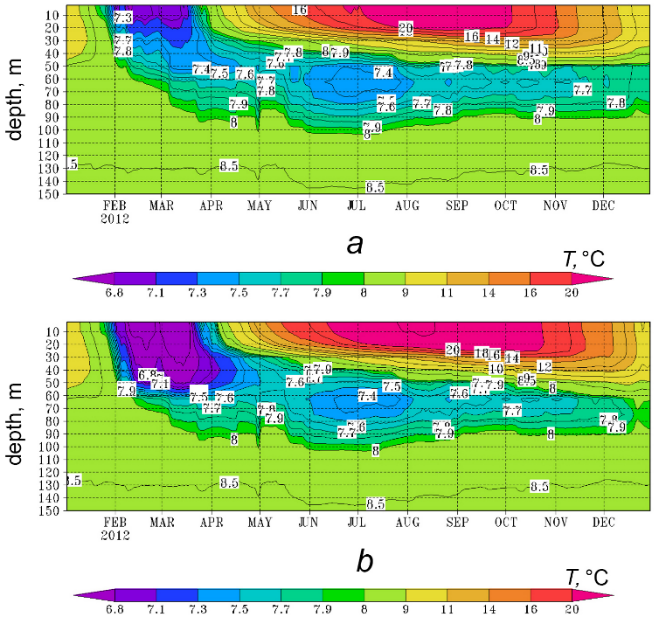


F i g. 4. Sea temperature (°C) spatial distribution on March 15, 2012: *a*, *d* – based on the reanalysis data including sea surface temperature assimilation; *b* – based on satellite data; *c*, *e* – based on the reanalysis data without sea surface temperature assimilation; above – on the surface; below – on the 20 m horizon

The spatial distributions of the surface temperature in summer, shown in Fig. 5, *a* and *b*, are similar. Structures with elevated temperatures are distinguished in the western water area of the sea and in the area oriented in the meridional direction eastward of Sinop. Areas with low sea temperatures (~ 22.5–23.5 °C) are visible in an almost meridional direction to the south-west of the Crimean Peninsula. Note also the coincidence of the upwelling areas on both maps: in the Kalamita Bay, off the coast of Novorossiysk, Tuapse and Anatolia (westward of Sinop). The structure of the temperature fields at 10 m horizon is the same as at 20 m horizon (Fig. 5, *a*), which characterizes the UML. The surface temperature, reconstructed in the reanalysis of hydrophysical fields without SST assimilation in the model (Fig. 5, *c*), turned out to be lower than that obtained from the data of satellite observations and from the reanalysis data with the SST assimilation. Increased values are observed in the western part of the basin, which is consistent with the data of satellite observations.

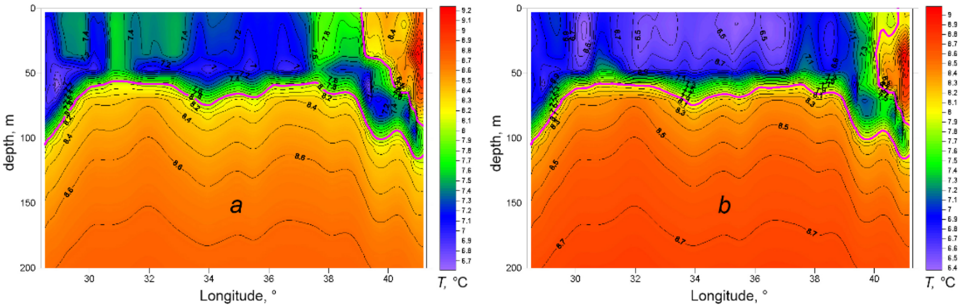


F i g. 5. Surface temperature (°C) spatial distribution on July 2, 2012: *a* – based on the reanalysis data including sea surface temperature assimilation; *b* – based on satellite data; *c* – based on the reanalysis data without sea surface temperature assimilation



F i g. 6. Diagram of seasonal variability of the horizon-average daily temperature (°C) in the 0–150 m layer based on the reanalysis data for 2012: *a* – without sea surface temperature assimilation [5], *b* – with sea surface temperature assimilation

The phenomenon inherent in the Black Sea – CIL – can be used to verify the results of water temperature reconstruction by means of SST assimilation in the model. This is confirmed by the diagram of the seasonal variability of basin-averaged daily temperature values in the upper 150-m layer, constructed from the data of two numerical calculations (Fig. 6). In Fig. 6, *b*, it can be seen that the sea water cold content in 0–60 m layer in February, March and early April is significantly higher than in the version of calculations without SST assimilation in the model (Fig. 6, *a*). In the remaining months, the distributions of averaged temperature within the CIL, outlined by 8 °C isotherm, are similar in both calculations due to the assimilation of temperature pseudo-measurements three-dimensional fields in 50–500 m layer by adaptive statistics method. However, there are also some differences. The consequence of SST assimilation in the model is an increased temperature in May – December on the surface and in 0–20 m (May) and 0–40 m (December) layers. Therefore, in the variant of reanalysis with SST assimilation in October – December, the CIL cold content is somewhat lower (Fig. 6, *b*).



F i g. 7. Temperature (°C) distribution at the vertical section along 42.685° N on 15.03.2012: *a* – without sea surface temperature assimilation [5], *b* – with sea surface temperature assimilation

Now we are to dwell on the analysis of the temperature distribution in 0–200 m layer on 03.15.2012 in the section along 42.685° N. In Fig. 7, *a*, which shows the results of temperature calculations without SST assimilation, it can be seen that during this period the process of replenishment and renewal of the sea CIL was actually completed. The temperature of cold waters of 0–50 m surface mixed layer is within 7.0–7.8 °C range. Fig. 7, *b* indicates that the SST assimilation in the model manifests itself in a decrease in the surface mixed layer water temperature. Its values vary mainly within the range of 6.5–6.7 °C. As the analysis of the temperature distribution on similar sections on 15.04.2012 shows, in April, in both variants of the calculations, the "locking" of the cold intermediate layer is observed. It manifests itself in the warming up of the sea surface layer with the formation of a seasonal thermocline and a clearly expressed CIL. The water temperature in the seasonal thermocline in the variant of the calculation with the SST assimilation in the model is somewhat lower (8.2–9.2 °C) than in the variant without its assimilation (8.2–9.6 °C).

Conclusion

In this work, the SST assimilation algorithm, together with the temperature and salinity profiles reconstructed from altimetry data, is implemented. When implementing the satellite SST assimilation algorithm in the model, the UML depth, estimated from the vertical water temperature profile, was used, since the vertical mixing parameterization by Pacanowski – Philander approximation provides direct identification of the UML depth.

Analysis of the temperature profiles obtained in the forecast calculation for 2012 and from the measurements of the *Argo* floating buoys made it possible to obtain a simple criterion for determining the mixed layer depth – temperature gradient at this horizon is more than 0.017 ºC/m.

Joint assimilation in the model of three-dimensional fields of seawater temperature (salinity) pseudo-measurements by adaptive statistics method and SST observations, obtained from satellite data, within the UML depth by means of model temperature relaxation to the observed one with 5 days relaxation coefficient, provided the reconstruction of the hydrophysical fields for 2012 with an acceptable accuracy.

The maximum value of the year-averaged RMS deviation of reconstructed temperature fields from those measured at hydrological stations and *Argo* buoys was obtained at 20 m horizon and is equal to 4.44 ºC, which is ~ 12% less than the calculation without SST assimilation. The maximum RMS deviation for the temperature in January – April, December was observed at 40 m horizon and is equal to 1.02 ºC. This period is characterized by the correspondence of calculated values of the mixed layer depths to the observed and reduced values of the RMS deviation. The largest RMS deviation values were obtained in summer and autumn, when the observed UML thickness is minimal. Note that in this work, for creating the most economical approach to assimilation of observations, we used Pacanowski – Philander formula adapted for the Black Sea. However, in the work of other authors [23] during the reanalysis of the Black Sea fields for 1993–2012 with SST assimilation in the MHI model using Mellor – Yamada turbulence model, the maximum value of temperature RMS deviation for winter turned out to be 0.6 ºC at 50 m depth and for summer 2.8 ºC at 20 m depth. A noticeable difference between the obtained RMS deviation values in our calculation, as noted above, is associated with the special conditions of the summer thermocline formation in 2012.

Comparison of the surface temperature (reconstructed in the reanalysis) maps with the same *SST*, *PODAAC* (*NASA*) maps in different seasons of 2012 showed that the increased and decreased temperature values in certain sea areas are well correlated with each other. Summer upwelling zones in Kalamita Bay, off the coast of Novorossiysk, Tuapse and Anatolia (westward of Sinop) also coincide on both maps.

The diagrams of seasonal variability of the basin-averaged daily temperature values in the upper 150-m layer, as well as latitudinal sections constructed from the data of two numerical calculations (with and without SST assimilation in the model), can be used to verify the reconstructed sea water temperature. The sections showed that the cold content of sea waters in 0–60 m layer in February, March and early April turned out to be significantly higher in the version of calculations with SST assimilation, which corresponds to the observational data. At the same time, the consequence of SST assimilation in the model was an increased temperature in May – December period both at the sea surface and in 0–20 m layers in May and 0–40 m in December.

The performed study shows that the proposed methodology for assimilation of seawater temperature and salinity pseudo-measurements in the model using Pacanowski – Philander parameterization, supplemented by the satellite SST assimilation, provides an opportunity to satisfactorily describe the hydrological fields in the entire thickness of the Black Sea. In order to assess the efficiency of Pacanowski – Philander parameterization application on climatic scales, it is advisable to compare it with Mellor – Yamada model used in [23], calculated for 1993–2012. At the same time, one should consider the possibility of using season-dependent coefficients in the Pacanowski – Philander parameterization to describe better the interannual variability of the summer thermocline characteristics in the Black Sea.

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Gennadiy K. Korotaev – analysis and synthesis of research data; correction of the paper; consulting support

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