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Accuracy of the reconstructed temperature in the Black Sea upper layer from nowcasting/forecasting systems

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Abstract. Verification of the Black Sea temperature in the upper layer from three leading prognostic systems is carried out using in-situ measurements and satellite sea surface temperature (SST) observations. Preliminary accuracy estimates are compared between the systems allowing a choice of a strategy for developing a new Black Sea nowcasting/forecasting system. It needs additional tuning of the ocean circulation model used, improvement of the satellite temperature assimilation procedure and implementation of the procedure for assimilation of observed temperature profiles.

1. Introduction
The Black Sea is an almost closed basin connected to the Marmara Sea and Azov Sea through the fairly narrow Bosporus and Kerch straits, respectively. An important feature of its stratification is the presence of a two-layer structure with sharp pycnocline (halocline) at depths of 200 – 300 m. In this layer the processes forced by the atmosphere over the basin are mostly manifested. The Black Sea plays an important role for the region countries. The baising is a major transport channel and a fishing area. Mild climate allows the development of recreational resources. Significant damage for the cities on the Black Sea coastal area can be caused by dangerous phenomena and human activities. Therefore, for successful use and development of mentioned resources, assessment of the impact of industrial and natural disasters requires high-quality and modern forecasting system of the sea physics.

A number of scientific projects of EU Framework Programs FP 6 and FP 7 in the beginning of 2010-s led to the development of Marine Forecasting Centers network in Europe. One of the main results of such systems (i.e. product) are oceans and seas state parameters, reconstructed by means of numerical ocean modeling and data assimilation for different time periods (nowcasts, forecasts, hindcasts). The main requirement for the products provided is accuracy, i.e. numerical simulation allows accurate reproduction of dynamics and thermodynamics of the seas and oceans. An example of such a system is the Black Sea Marine Forecasting Center (BS MFC, http://mis.bsmfc.net) created in the MHI [1]. Later similar regional systems were merged into a single Marine Environmental Monitoring Service of the Copernicus project (CMEMS, http://marine.copernicus.eu/). Since 2014, the BS MFC left the service and operates apart from the service. European analog was implemented instead.

The results of the BS MFC system quite adequately reproduce the synoptic processes in the Black Sea. However currently available satellite measurements indicate the presence of meso- and sub-mesoscale variability in the coastal and shelf zones of the sea, as well as in its deep-basin part. It
causes the implementation of a new version of the nowcasting/forecasting system with the further development of the BS MFC using parallel computing on high-performance computers. It will improve the horizontal spatial resolution of the numerical model to raise the quality of reconstructed fields. In addition, the problem to solve will be improvement of the accuracy of the vertical structure reproduction. Therefore, an important issue is the quality of currently available systems. Both the horizontal spatial variability and the vertical structure in the upper layer in the products provided are important. Another important question is comparison of characteristics of the product quality between different forecasting systems.

In this paper, the quality of model products for the Black Sea basin from three leading forecasting systems is studied. The results of verification procedure for one of the main hydrophysical parameters – sea water temperature, are presented. The verification is carried out by comparing the model products with in-situ profiling floats data (accessed on 8 January 2018) and satellite SST L3S processing level (SST_BS_SST_L3S_OBSERVATIONS_010_013, access 20 February 2018) provided by CMEMS (http://marine.copernicus.eu/). Estimates of the product accuracy for the selected nowcasting/forecasting systems are presented, as well as methods for analyzing the data.

2. Materials and methods
For analysis in this paper we use daily physical nowcasts of the Black Sea state described in table 1.

Table 1. Forecasting centers and products reviewed in this paper.

| №  | Product                                           | Forecasting center | Ocean model | Spatial resolution         |
|----|---------------------------------------------------|--------------------|-------------|---------------------------|
| 1  | BLACKSEA_ANALYSIS_FORECAST_PHYS_007_01            | BSMFC              | MHI [2]     | 2/45°×11/180° (~5 km)    |
|    |                                                  |                    |             |                           |
| 2  | BLKSEA_ANALYSIS_FORECAST_PHYS_007_01             | CMEMS              | NEMO v3.4 [3] | 1/36°×1/27° (~3 km)     |
|    |                                                  |                    |             |                           |
| 3  | GLBa0.08                                          | NRL HYCOM         | HYCOM [6]   | 1/12° (~9 km)             |
|    |                                                  |                    |             |                           |

Note that presented systems are quite different, so the accuracy values given below cannot be a quality estimation of the ocean circulation models used to perform numerical simulations. The core of the BS MFC operational system is the z-coordinate ocean circulation model [2] which is an own development of MHI. The data assimilation system is based on the optimal interpolation (OI) procedure of along-track satellite altimetry and retroaction of modeling results to satellite SST. In the deep-basin part yearly averaged temperature and salinity profiles based on observations are assimilated.

The Black Sea operational system implemented in the framework of CMEMS operates in the Euro-Mediterranean Center for Climate Change (CMCC). It is based on the NEMO v3.4 modeling framework. The reconstructed marine physical parameters have about 3 km spatial resolution [4] (see table 1), which is somewhat higher than from BS MFC. The product is available on 31 unevenly spaced vertical levels. The observational data are assimilated by means of the 3D variational assimilation procedure (3DVAR) [5]. It allows one to assimilate satellite temperature, profiling floats data and along-track sea level anomaly (SLA).

One more product GLBa0.08 is obtained at the Naval Research Laboratory (NRL). Their system is based on HYCOM modelling framework. The main feature of this model is a hybrid vertical coordinate: isopycnic in the open ocean, geopotential in the upper mixed layer and terrain-following on the shelf. The product is provided using 32 vertical levels. The system assimilates a large number of observations, described in detail in [7]. For verification study we use model products for the period
of 2016 – 2017. Mean (Δ) and root – mean – square (RMS) differences between nowcast temperature and measurements are analyzed. They are obtained according to $Δ = M[T^a - T^{obes}]$, and $RMS = \{M[(T^a - T^{obs})^2]\}^{1/2}$, where $T^a$ is nowcast temperature (analysis), $T^{obs}$ is observed temperature, $M[\cdot]$ is an averaging operator. For these metrics averaging was calculated for different layers of the basin and within different time windows for the representativeness and visualisation. While comparing reconstructed SST to the satellite one we use remapping to the grid of the observations.

3. Results

The verification results showed sufficiently high accuracy of the reconstructed sea water temperature in the upper layer for the reviewed systems. There are a number of peculiarities in the analyzed products described below. The differences in products are mostly noticed in the layer of 0 – 100 m. In the layer of 10 – 30 m in the spring – summer period the CMEMS and BSMFC systems exceed the observed temperature. The CMEMS system significantly overestimated it in 2016. The HYCOM product in this layer is below observed values, which can be the reason of low heat fluxes from the surface forcing. The period of winter cooling for this layer is reproduced rather adequately in all three systems, but has its own features noted below. Deeper in the layer of 30 – 50 m the CMEMS and BSMFC systems vice versa give temperatures lower comparing to observation, in contrast to HYCOM. Large bias was shown by CMEMS in 2016.

Figure 1 represents the quality of the products in the layers of 10 – 30, 30 – 100 and 100 – 300 m. It can be seen that accuracy behavior corresponds to the bias. In the summer-autumn an accuracy decline is observed in the layer of 10 – 30 m for the investigated systems. Here RMS exceeds 2 °C (figure 1, a). In the period of winter-spring convection the error in temperature for all the systems decreases. In the period of August – September, the products of BS MFC represent the lowest accuracy in this layer (figure 1, a). For the rest of the time, the accuracy of temperature reconstruction is close for the systems. A similar behavior of RMS with some time lag of the maximum position to November is observed in the layer of 30 – 100 m (figure 1, b). By this time the accuracy falls for HYCOM product (RMS maxima in October). From November to the beginning of winter convection we can see higher RMS values for the CMEMS products. In HYCOM system very low accuracy in the layer of 100 – 300 m was observed in the second half of 2016. Probably, the vertical turbulent mixing procedure used in the model is not tuned adequately. CMEMS products are more accurate in this layer comparing to the rest (low values RMS except the second quarter of 2017) (figure 1, c). Thus, the assimilation of only yearly averaged profiles in the deep-basin does not allow us to sufficiently improve the quality of the temperature analysis in the BS MFC deeper than 100 m.

The analysis results of the reconstructed SST fields in the systems are presented in figures 2 and 3. The BS MFC and CMEMS systems mostly overestimate the SST values, except for the period of September-November 2016 (figure 2, a). The SST accuracy decreases starting from October, and by the middle of the winter convection it raises. The HYCOM system gives lower SST values from mid-summer to September, where the product accuracy is low. This was mostly noticed in 2016. For the rest of the time accuracy is close comparing to the products of CMEMS and BS MFC. Lowering of HYCOM SST can be caused by low temperature in the layer below( 0 – 30 m) (figure 1, b) and model of vertical turbulent mixing. The minimum bias in the products and satisfactory accuracy were observed in the spring and early summer of 2017 (RMS$_{BSMFC} \approx 0.4$) (figure 2). An example of SST fields during this period is represented in figure 3.

It can be seen that HYCOM product has a close spatial variability to satellite data, despite the low resolution. In general, this SST looks a bit lower than the satellite data (figure 2, a, figure 3, d). Cold waters come to the surface as a result of coastal upwelling near the coasts of Crimea and Turkey (figure 3, b). Also lower temperatures are observed on the northwestern shelf of the basin. The CMEMS product also has a similar to observed spatial variability (figure 3, c). The sea water temperature values in deep-basin part are obviously increased here (figure 3, a; figure 3, c). We note that during the period of study SST fields of this product has perturbations similar to waves in some parts of the basin (figure 3, c, zoom in the upper right corner). We cannot surely confirm if this is the
result of a poor tuning of a numerical ocean model (i.e., numerical instability) or assimilation procedure feature (i.e., perturbations associated with the model shock after the correction of simulation results). Obviously these perturbations are likely to introduce a systematic error to the reconstructed SST.

Figure 1. Weekly averaged basin mean RMS of «nowcast minus observations» from in-situ data in the Black Sea upper layers: (a) 5 – 30 m, (b) 30 – 100 m, (c) 100 – 300 m.

The SST from the BS MFC looks smoother as compared to the rest products (figure 3, a, the zoom in the upper right corner), which can be explained by the assimilation procedure and small weights of observational data during the analysis calculation. A more detailed analysis of the BS MFC SST fields spatial variability is beyond the scope of this paper. Nevertheless, the main dynamic structures from satellite SST are represented in the reconstructed field here. This product has somewhat more accurate SST values than the rest ($\text{RMS}_{\text{BS MFC}} \approx 0.54$, $\text{RMS}_{\text{CMCC}} \approx 0.6$, $\text{RMS}_{\text{CMCC}} \approx 0.65$) (figure 2, b).

Figure 2. Weekly averaged difference (a) and RMS (b) «nowcast minus observations» based on satellite data and reconstructed SST

4. Conclusion
Using in-situ measurements and satellite data we verified temperature in the upper layer for three leading prognostic systems for the Black Sea basin. Results show a number of important questions for implementation of a new nowcasting/forecasting system of the Black Sea state. In particular, the BS
MFC and CMEMS systems overestimate temperature on the surface and in the layer of 10 – 30 m. The temperature of HYCOM product is below the observations. Quantitatively, the SST from BS MFC for the whole basin is slightly better than from other systems ($\text{RMS}_{\text{BSMFC}} \approx 0.54$). The minimum bias of SST products and satisfying accuracy were observed in the spring and early summer of 2017. The fields reconstructed in the BS MFC are rather smooth comparing to other products and additional analysis of spatial variability is required. In layer of 0 – 30 m in the period of August – September low accuracy is obtained in the BS MFC products, in the rest of the time the accuracy of temperature profiles in three systems is comparable. Deeper, in layer of 30 – 100 m CMEMS system lowers the temperature and HYCOM overestimates it. The BS MFC system is more accurate here. The maximum error in this layer for all three systems is shifted to November.

Figure 3. Sea surface temperature on June 17, 2017: (a) BS MFC, (b) HYCOM, (c) CMEMS. Zoom of a region marked with a dashed line in the upper right corner in figures (a) and (c). The color map norm of zoomed fields is changed for representativeness.

The presented study allow us to reveal that development of a new nowcasting/forecasting system for the Black Sea state needs additional tuning of the ocean circulation model used, improvement of the satellite temperature assimilation procedure and implementation of the procedure for assimilation of observed temperature profiles.

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