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MARINE PHYSICS

Impact on Oceanic Dynamics from Assimilation of Satellite Surface Height Anomaly Data into the Hybrid Coordinate Ocean Model (HYCOM) over the Atlantic Ocean

C. A. S. Tanajura[a, b, c], *, L. N. Lima[b], **, and K. Belyaev[a, d, e], ***

[a] *Instituto de Fisica, Universidade Federal da Bahia, Salvador, Brazil*
[b] *Centro de Pesquisa de Geologia e Geofísica, Universidade Federal da Bahia, Salvador, Brazil*
[c] *Department of Ocean Sciences, University of California, Santa Cruz, USA*
[d] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia*
[e] *Keldysh Federal Research Centre for Applied Mathematics RAS, Moscow, Russia*
**e-mail: cast@ufba.br*
***e-mail: Leonasclima@gmail.com*
****e-mail: kb@sail.msk.ru*
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Abstract—Observed along-track data of sea surface height anomalies (SSHAs) over the Atlantic Ocean from the Jason-1 and Jason-2 satellites were assimilated into the Hybrid-Coordinate Ocean Model (HYCOM) with the Ensemble Optimal Interpolation scheme (EnOI). The impact of assimilation of SSHA with focus on oceanic dynamics was investigated. Time series of analyzed and forecasted values were compared with a model free run with the same forcing but without assimilation. In addition, the results were compared with an independent run, the so-called HYCOM + NCODA analysis from the US Navy. The study shows that the assimilation technique with some modifications allowed substantial improvement in the 24 h ocean prediction by reducing the forecast errors in comparison with the free run. It is also shown that the analyzed sea surface fields contain mesoscale and synoptic variability, which are poorly seen in the free run.

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1. INTRODUCTION

This work continues a study whose results are given in [4]. Here we analytically treat the impact resulting from assimilation of observational data, specifically, the impact of assimilation of ocean level anomalies (OLA) on the calculated dynamic characteristics of the ocean, such as current velocity and the thickness of the constant density layer. Description of such impact is of primary importance, because satellites make it possible to obtain a large amount of data concurrently, covering vast oceanic regions; however, at the same time, the dynamic characteristics are virtually unobservable. Therefore, it is natural to try to understand and calculate the relations between the observable features (e.g., the OLA) and the ocean's dynamic features, such as the current velocity and homogeneous density layers. In the present study, the assimilation is performed along satellite ground tracks in the Atlantic Ocean for the OLAs considered as the most significant characteristics for describing the surface and subsurface dynamics of the ocean.

Study [4] demonstrates the impact of assimilation of the OLA on the thermohaline structure of the ocean and compares the temperature and salinity profiles observed. The latter has been taken from moored buoys of the PIRATA (Pilot Research Array in the Tropical Atlantic) experiment and from ARGO drifters. Meanwhile, an extremely important question has been left "off-screen," namely, the impact of OLA assimilation on the unobservable characteristics of the ocean, such as the current velocity, and on the structure of vertical layers of the ocean, specifically, vertical layers of constant density.

In this study, we demonstrate how the assimilation of OLA impacts the structure of the dynamic characteristics of the ocean and quantitatively assess such impact. In addition, we compare the calculation results to independent information obtained from the HYCOM + NCODA model in the United States (Miami) [6].

The data assimilation procedure is described in detail in [4]. Here we emphasize only that data assimilation is accompanied by the concurrent impact of observations (OLA in our case) on all calculation values by means of the constructed covariation functions. This distinguishes our algorithm from others. In the

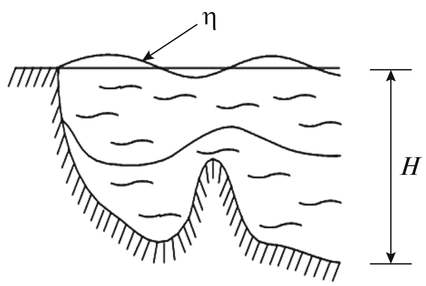

Fig. 1. Structure of isopycnics in HYCOM model. η is ocean level; *H* is ocean depth. Density interface given in middle.

latter, one or several calculation values are corrected at the outset and the remaining model characteristics change during subsequent calculations after the corrected value is entered into the model. In the latter case, the change of a single value after assimilation and substitution of it into the model leads to dummy perturbations and disruption of the balance, which requires extra time for model adaptation.

Here we use the well-known model HYCOM v. 2.14. This is a so-called isopycnic ocean dynamics model, in which the entire ocean from the surface to the bottom is divided into layers of equal density. Thus, any ocean characteristic is referenced with respect to the *k*th layer of constant density. The corresponding layout is based on original works [5, 6]. The structure of a vertical section in the model is shown in Fig. 1.

The layer structure changes with data assimilation, which is accompanied by changes in current characteristics inside a layer. It is important to understand exactly how this happens. This is done in the present study when assimilating the OLA data from the AVISO archive based on the procedure described in detail in [4]. This is the subject of the present study.

It should be noted that there are few works on the assimilation of OLA data from satellites and their impact on directly unobservable characteristics of the model. This is mainly due to the fact that it is difficult to evaluate the reliability of fields obtained because of assimilation and, moreover, to compare them with something. Therefore, it is worth mentioning the works from the HYCOM + NCODA experiment [6] along with studies by Russian authors [2, 3].

2. EXPERIMENTAL AND RESULTS

The experiments for assimilation of satellite observations started on January 1, 2011, and lasted 90 days. The correction was carried out successively every second day, and the actual observations were used during the day of assimilation. Prior to assimilation, the satellite data were filtered by the so-called sliding average according to the formula

$$\overline{h}_i = (2k+1)^{-1} \sum_{j=i-k}^{i+k} h_j,$$

where $\overline{h}_i, h_j$ are corresponding level of the ocean surface before and after filtering, and i, j change from 1 to N_{obs}. In what follows, the filtered values $\overline{h}_i$ were used only in the experiments (Fig. 2).

This paragraph shows the impact of assimilation of OLA on the dynamic quantities of the model, such as the horizontal current velocity components, the pressure field, and the thickness of the constant density layer (isopycnic layer). The HYCOM model is isopycnic. Therefore, the thickness of the constant density layer is variable at every point in space and it also changes in time. The currents are directly coupled with the level of the ocean surface. Therefore, we can naturally expect a significant impact when assimilating this quantity (its anomalies). The cross section of the absolute current velocity in the horizontal plane is shown in Fig. 3. Maps (a, b) in Fig. 3 represent the

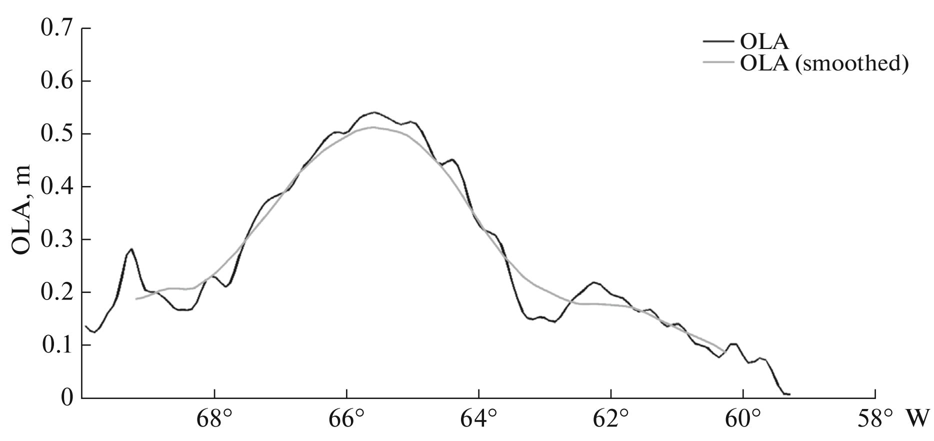

Fig. 2. Behavior of initial and smoothed OLA along track on last day of integration April 3, 2011.

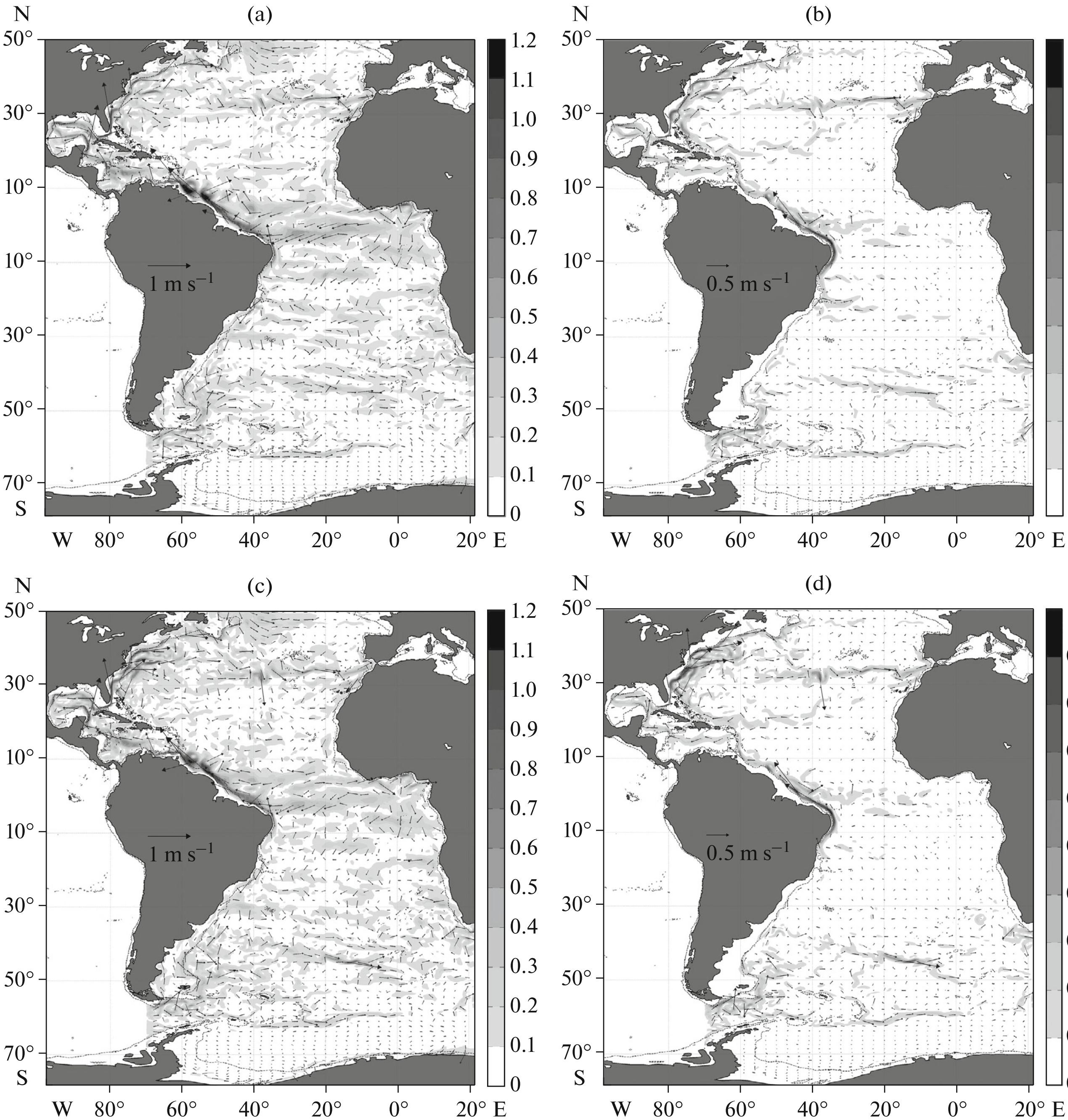

Fig. 3. Absolute current velocities in horizontal plane on April 3, 2011. (a) Analysis 20 m, (b) analysis 200 m, (c) control 20 m, (d) control 200 m.

patterns of currents at 20 and 200 m for analysis, while maps (c, d) are given for control. All values have been calculated for the last day of integration. It is evident from Fig. 3 that assimilation substantially intensifies the currents in the Gulf Stream and improves the visibility of two branches at both 20 and 200 m. The absolute velocities exceed 1 m/s. These velocities are much weaker in Figs. 3c and 3d for the control experiment; velocities higher than 1 m/s are distinguishable only in the north of the Brazil current. In contrast, the velocities on the surface of the equatorial current are more visible in the control experiment, and their estimates are closer to 60 cm/s, in contrast to the assimilation results where they were less than 50 cm/s. The main structural peculiarities in the results of both experiments are similar to each other. The results are well consistent with calculations from other models [1].

Figure 4 shows the vertical cross sections of the vertical zonal component of the velocity along the equa-

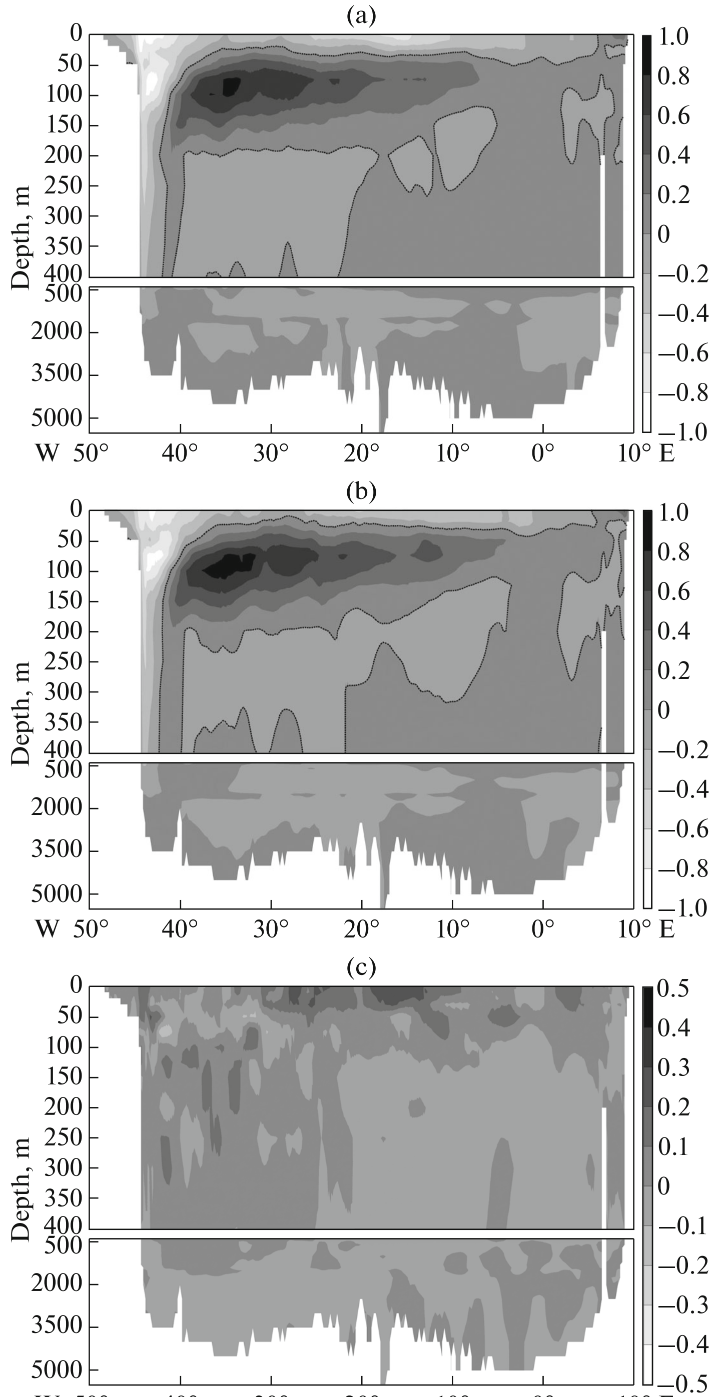

Fig. 4. Vertical cross sections of zonal velocity component of current along equator on April 3, 2011. (a) Control, (b) analysis, (c) difference analysis minus control.

tor: (a) control, (b) analysis, and (c) their difference. It is evident that the model underestimates the subsurface countercurrent with respect to assimilation and at the same time overestimates the surface equatorial current. The difference "assimilation minus control" is positive everywhere, while the maximum of this difference is 0.5 m/s and is located near 15° W. Both the assimilation and control calculation demonstrate that the surface current along the equator does not penetrate African coastal waters but begins roughly at 5° E. This contradicts the results of HYCOM-NCODA calculations [6] (see below) but corresponds to the results in [7].

Figures 3 and 4 are comparable to Fig. 5 based on calculations at the of US Naval Research Laboratory

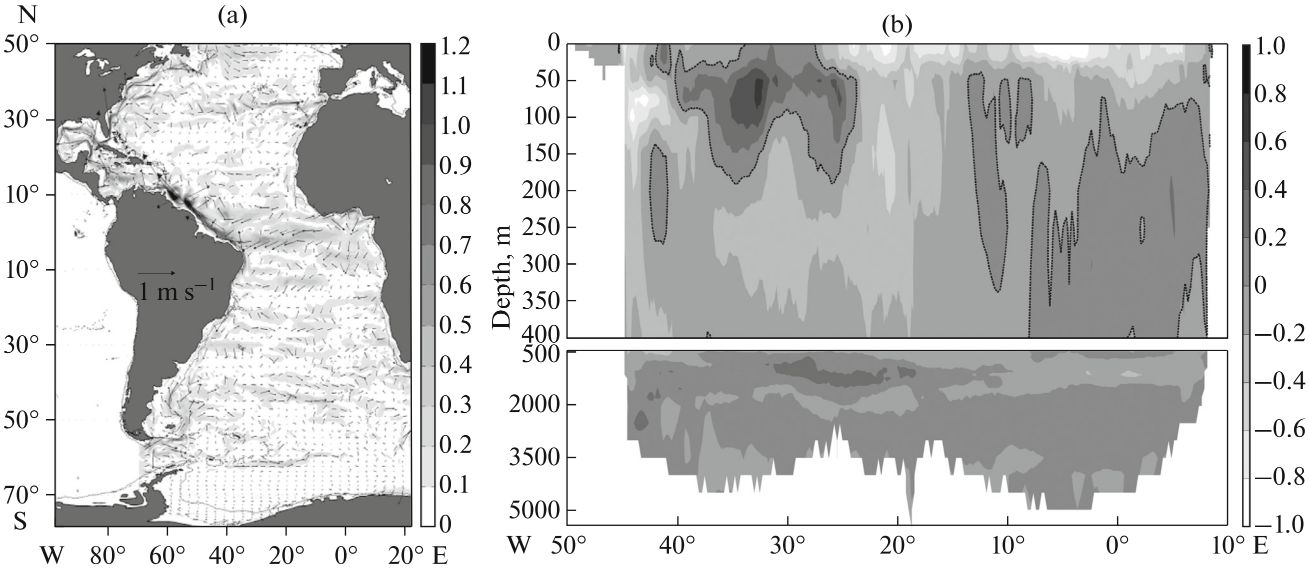

Fig. 5. Current velocities from HYCOM + NCODA analysis data on April 4, 2011 (a) 20 m, (b) cross section of zonal velocity component along equator.

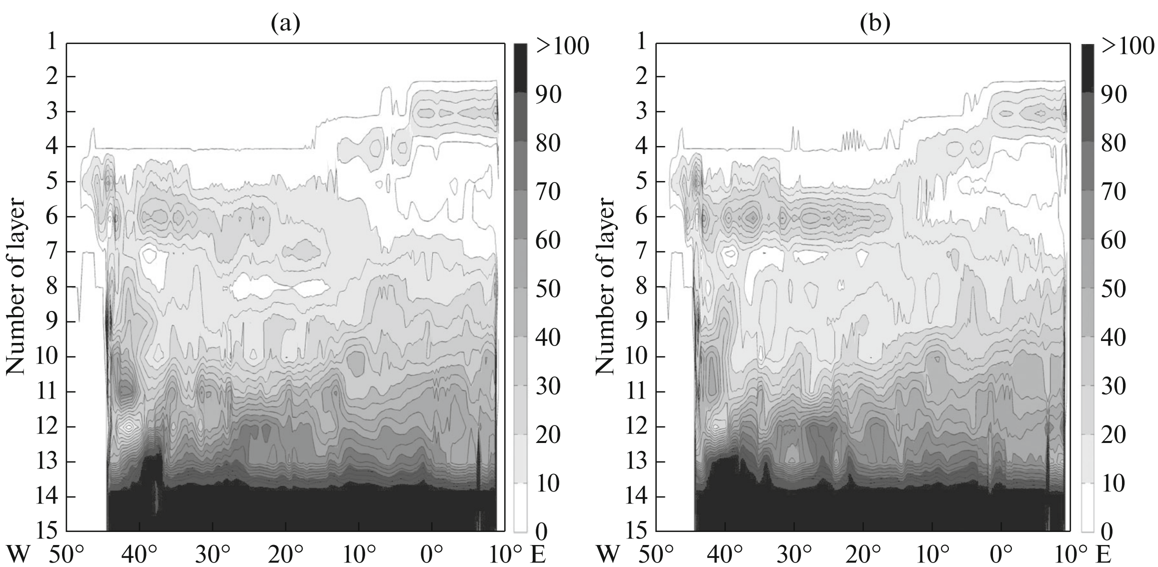

Fig. 6. Thickness of constant density layers along equator on April 3, 2011. (a) Control, (b) analysis.

according to so-called HYCOM-NCODA analysis [6]. Similarly to Fig. 3, Fig. 5a shows the absolute velocities at 20 m and Fig. 5b shows the vertical cross section of the zonal velocity component along the equator. The main differences from Fig. 3 are the Gulf Stream and equatorial zones. According to the HYCOM + NCODA analysis, the Gulf Stream is composed of a single branch in contrast to the pattern in Fig. 3. In addition, the surface equatorial current penetrates the African coastal zone but does not approach the shores of Brazil along the equator. Numerically, the pattern in Fig. 5 corresponds better to assimilation than to the control calculation. Assessments of the standard deviation between current velocities (zonal component) for the assimilation and control calculation and for the HYCOM + NCODA calculations (Figs. 4a, 4b, 5b) yield 28 and 37% respectively. These differences are not shown, because all the structures are present in Figs. 4 and 5b.

A peculiar feature of the HYCOM model is its isopycnic structure, i.e., subdivision into layers of constant density (Fig. 1) [5]. Therefore, it is particularly interesting to assess the impact of OLA assimilation on changes in this structure. Figure 6 shows the assimilation and control of thicknesses for each of the 21 layers along the equator; Figs. 6a and 6b correspond to the analysis and control, respectively. The main difference is evident in the case of level 6, which becomes thinner and longer due to assimilation. In addition, assimilation leads to a certain randomness of the entire inner zone between levels 6 and 12. The core with a small thickness in the upper part of Fig. 6 (levels 5 and 6) decreases. A smaller core leads to intensification of the current, which is consistent with earlier results. Meanwhile, the hydrostatic pressure in the layer also increases, which results in intensification of gradient currents.

7. CONCLUSIONS

Our work shows that OLA assimilation substantially impacts the behavior of all calculable characteristics in the HYCOM model. This impact is most significant for such dynamic characteristics as currents velocity, layer thickness, or pressure. The same impact affects the temperature, salinity, and other tracers to a lesser but not negligible degree. The study revealed that even the indirect impact of OLA substantially intensifies the model dynamics of the ocean after several consequent assimilations, particularly at the synoptic and mesoscales. In addition, it was shown that it is necessary to correct the initial displacement between observations and calculable quantities.

The dynamic quantities are very sensitive to assimilation of OLA data. The currents are intensified by at least 30% relative to the control calculation. The difference can be more than 100% after recalculation into energy characteristics. In addition, assimilation of OLA significantly enriches the patterns of motion by adding the new features into the dynamics of mesoscale eddies, meanders, and shortwave motions in the ocean.

Assimilation of OLA data is a necessary part of the operational system of data assimilation when forecasting the state of the ocean. This is important from the viewpoint of both theory and practice.

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