Simulation of the global ocean thermohaline circulation with an eddy-resolving INMIO model configuration

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Abstract. In this paper, the first results of a simulation of the mean World Ocean thermohaline characteristics obtained by the INMIO ocean general circulation model configured with 0.1 degree resolution in a 5-year long numerical experiment following the CORE-II protocol are presented. The horizontal and zonal mean distributions of the solution bias against the WOA09 data are analyzed. The seasonal cycle of heat content at a specified site of the North Atlantic is also discussed. The simulation results demonstrate a clear improvement in the quality of representation of the upper ocean compared to the results of experiments with 0.5 and 0.25 degree model configurations. Some remaining biases of the model solution and possible ways of their overcoming are highlighted.

1. Introduction

Ocean general circulation models have been used for half a century for the numerical investigation of ocean dynamics and its variability on a wide range of spatial and temporal scales, from weather forecast to climate change assessments. During this period, the model resolution has increased by two orders of magnitude (from several degrees to hundredths of a degree), and the complexity of physical parameterizations has also greatly increased. Nowadays the development of seamless models which are able to work on various spatio-temporal scales [1] is especially important.

This work follows the line of the CORE-I [2] and CORE-II [3] projects, and continues the studies of [4,5], which discussed some qualitative characteristics of the World and Atlantic Oceans general circulation simulated by the INMIO model with a resolution of 0.5° and 0.25°. The new model configuration is based on [6] and incorporates several modernizations allowing one to perform multi-year numerical studies of ocean dynamics with a resolution of 0.1°. According to some works, this resolution is the minimum necessary requirement for reproducing ocean mesoscale eddies and dynamical structures, such as western boundary currents [7,8] and Greenland-Scotland Ridge overflows [9]. Global ocean simulations of such resolution require powerful supercomputers and scalable numerical methods. Software tools that provide an environment for such calculations were created within the framework of studies [10,11] and include, first of all, a fully parallel coupler and I/O procedures, as well as effective high-level means of interprocessor communication. The use of explicit numerical methods for the ocean dynamics equations approximation allowed us to achieve a high scalability level of the model program code with a trivial two-dimensional decomposition of the computational domain. However, it demanded greater attention towards stability issues, particularly to self-consistency of numerical schemes on the difference level. The current version of the 0.1° INMIO
model configuration is able to stably perform calculations with no Laplacian viscous terms, with small heat and salt diffusivities and a flux-corrected transport scheme for the tracer equations.

The purpose of this work is a primary study of the eddy-resolving ability of the model to reproduce the large-scale thermohaline characteristics during the first years of calculations of the spinup of dynamic processes in the upper layers of the model ocean. For this, a 5-year numerical experiment has been performed, and the results of the last year have been analyzed. The main method of analysis consists in a comparison of the annual mean model temperature and salinity fields with the WOA09 climatology data [12,13].

2. The World Ocean model and experiment setup

The INMIO model implements the three-dimensional primitive equations system of ocean dynamics with the Boussinesq and hydrostatic approximations by means of a finite-volume method on an arbitrary locally-orthogonal B-type grid and in vertical z-coordinates. The atmosphere-ocean interface is described by a nonlinear free-surface condition with explicit formulation of heat, momentum, and water fluxes calculated by the CORE boundary layer bulk formulae [14]. The lateral boundaries impose free slip and zero flux conditions, and the bottom friction is parameterized according to a quadratic drag law. The sea ice is described by a thermodynamic model [15].

In this study, the momentum advection is calculated by a centered difference scheme and the tracer advection utilizes a scheme of flux-corrected transport [16]. The time derivatives are approximated by the leap-frog scheme with a periodic addition of an Euler step for contraction of the two numerical modes. For efficient use of computational resources, the fast barotropic dynamics is modeled separately from the baroclinic processes by means of a shallow-water-type system of equations [17] solved with a small step time and a numerical scheme utilizing a massively-parallel algorithm with overlaps [18]. To provide numerical stability, the momentum and tracer transport equations are appended by biharmonic filters. The vertical mixing is parameterized by the Munk-Anderson scheme with activation of convective adjustment in case of an unstably stratified water column.

The experiment setup of this work corresponds to the atmospheric boundary conditions of the CORE-II protocol for 1978-1982. A 3600×1800 horizontal grid is constructed according to a tripolar scheme [19] with poles in Siberia, North-Western Canada, and on the true South Pole, and has a resolution of 0.1° in the spherical part south of 60°N. The horizontal mixing coefficients are: zero for Laplacian viscosity, \(-18.89 \text{ m}^2/\text{s}\) for biharmonic viscosity on the equator with scaling proportional to the third power of the gridbox area square root, \(100 \text{ m}^2/\text{s}\) for the tracer diffusion on the equator with a linear scaling to the gridbox area square root. The shallow water equations viscosity and biharmonic tracer diffusivity are not used in this experiment. The background values of vertical viscosity and diffusivity are \(10^4\) and \(10^5 \text{ m}^2/\text{s}\), and the maximal values in places with small Richardson numbers are \(10^2\) and \(10^3 \text{ m}^2/\text{s}\), respectively. The time step is 4 min. for the baroclinic dynamics equations and 5 sec. for the shallow water equations of the barotropic processes.

The monthly mean continental runoff is defined as the precipitation spread over the ocean surface close to the coasts and river estuaries. To avoid a model sea level drift, a surface water flux normalization condition is applied, i.e. the global mean value is subtracted from the total water flux, \(\text{Prec} - \text{Evap} + \text{Runoff}\). The initial temperature and salinity conditions are taken from the annual mean WOA09 data, the ocean current velocities and sea ice cover are initialized as zero. The ocean bottom topography is interpolated from the ETOPO5 database [20] excluding the internal continental water reservoirs and the Black Sea. The sea surface temperature or salinity relaxation is not used.

3. Results of the numerical experiment

The distributions of ocean temperature and salinity can characterize the internal model dynamics and can be used to assess the quality of the simulated model currents, the vertical mixing processes, and the formation of water masses. Since the state of the ocean surface is closely related to the atmospheric
forcing and experiences strong interannual variation, and the deep model layers require longer periods of calculation for the spinup of dynamics, we consider for the initial analysis in Figure 1 the fields of annual mean temperature and salinity biases against the WOA09 data averaged over the upper 700-metre layer of the ocean, as done in [3,5].

Since the observational data used in the WOA09 climatology are generally smoothed, their use for verification of model solutions will be justified only on sufficiently large spatial scales. First of all, the INMIO model generally slightly heats the upper ocean layers, which is typical for the same-type z-coordinate models [2,4] and may be associated with parameterization errors of vertical mixing, in particular, with the viscosity of the transport scheme used. The positive temperature bias in the East Equatorial Pacific shows that the model reproduces well the strong El-Niño event of 1982-1983.

The intense jet streams of the Gulf Stream and Kuroshio are poorly resolved by the WOA09 data and, therefore, in the model solution bias map they are manifested in the form of narrow coastal cold tongues, until their separation from the continental slope. However, on the further path of these currents, quasi-zonally oriented biases of temperature and salinity, negative to the South and positive to the North, reveal inaccurate reproduction of the currents’ routes with typical deviation to the North. However, in comparison with an Atlantic simulation [5] of 0.25º resolution, the rate of warm and salty water deviation to the North has declined. On the contrary, the dipole temperature and salinity biases in the mid-latitudes of the Central Atlantic and the positive bias to the east of Iceland have not weakened with increased resolution compared to [5]. In [21], no relationship of these biases with errors of deep vertical mixing was found and, hence, we can assume that their occurrence is due to inaccurate modeling of the atmosphere–ocean interaction or atmospheric forcing errors of the CORE-II data, both causing errors in the simulated currents’ pathways.

The positive temperature and salinity biases off the western coast of South Africa are apparently due to the poor upwelling resolution caused by some errors of atmospheric forcing representation. The Antarctic Circumpolar and Agulhas currents, as well as the Falkland and Brazil currents confluence region, are places of intense mesoscale activity. Its quasi-stationary elements sustained by the model but not resolved in WOA09, such as jets and standing eddies, are clearly manifested on the temperature and salinity bias maps. Finally, the extensive salinity biases near the shores of some seas, especially in the Arctic, may require an improvement in the shelf vertical mixing and fresh water distribution parameterizations.

The vertical structure of the concerned temperature and salinity biases is presented in Figures 2 and 3, where their zonal mean distributions with latitude and depth are shown for the entire World Ocean and its basins reflecting the properties of large-scale water mass ventilation. In most cases, especially for salinity, the anomalies reach depths of about 500 m, indicating a characteristic depth scale of the layer that had spun up during the time of the model experiment. Deep-lying biases of heat and salt distribution in the 60-70ºN latitudes of the Atlantic Ocean may emerge from the overestimated intensity of deep convection, seen also in [21] and possibly caused by errors of surface temperature and salinity fields or incorrect representation of mixing in case of steep isopicnals [2]. On the contrary, the dipole bias in the North Indian Ocean may be caused by insufficient intensity of mixing.

The increased temperature on the latitudes of the Antarctic Intermediate Water in the Southern Ocean may be a result of the excessive mixed layer depths near the regions of Subantarctic Mode Water formation or incorrect subduction and isopical mixing of water masses in the area [2]. Typical maximum temperature biases are reached in the equatorial regions at a depth of 100-200 m. They appear as two cores with a diffused thermocline near the equator in the Atlantic, with a shift to the north in the Pacific and to the south in the Indian Ocean.
Figure 1. Temperature (a, °C) and salinity (b, psu) annual mean biases relative to the WOA09 data averaged over the upper 700 m ocean layer.
Figure 2. Annual mean temperature bias (°C) relative to the WOA09 data zonally averaged for the World (a), Atlantic (b), Indian (c), and Pacific (d) Oceans.

Figure 3. The same for salinity bias (psu).
To assess the quality of simulation for the annual cycle of ocean near-surface thermal characteristics, we consider the monthly mean surface temperatures and heat content (vertically integrated temperature) of the upper 250-metre ocean layer at a point of continuous ship observations, OWS Echo (35°N, 48°W). The monthly values of heat content are plotted against the monthly mean temperatures for the last year of the numerical experiment being considered, for the WOA09 monthly data, and also for the quasi-stationary solution of the INMIO model obtained in [4] with a resolution of 0.5°. The points of the hysteresis graph correspond to the months of the year, from January to December in the counterclockwise direction (Figure 4).

![Figure 4](image_url)

**Figure 4.** Seasonal heat content cycle at the OWS Echo site (35°N, 48°W) according to the WOA09 data and INMIO simulations of 0.5° and 0.1° resolution.

Both versions of the model reproduce well the phases of the seasonal heat content variability, while in [4] it was found that the phase errors in the model results often have the same order of magnitude as the differences between the climatological databases (in particular, between PHC3.0 and WOA2001). For the INMIO 0.5° configuration, significantly underestimated are the average heat content and its yearly amplitude, and, as for most of the models in [2], the maximum summer surface temperature. When using the model of 0.1° resolution, the first and third characteristics have almost coincided with the WOA09 climatology data. Since in the mid-latitudes the seasonal cycle of ocean heat content is primarily governed by the surface heat flux [22], better reproduction of the heat content is apparently associated with a better simulation of the upper ocean dynamics and, as a consequence, of the ocean-atmosphere interaction. In contrast to [2], it seems that correction of external forcing is not required. As for the autumn and winter heat content underestimated by the model, comparison with Fig. 1 allows us to conclude that it is likely caused by a shift of the warm Gulf Stream current to the north of the site being considered.

4. Conclusions

The numerical experiment performed within the framework of the CORE project is the first experience of analyzing the global thermohaline characteristics of the multi-year solution obtained using an eddy-resolving 0.1-degree INMIO model configuration. It has shown a noticeable improvement in the
quality of the model solution in the upper ocean layer compared to the previous calculations with 0.5- and 0.25-degree configurations. However, the problem of the deviation of the Gulf Stream and the Kuroshio currents to the north after their separation from the continental slope, as well as the inaccurate representation of the North Atlantic current in the subpolar gyre region, has not been completely solved. A detailed analysis of the atmospheric forcing data and mixing parameterizations on the continental shelf will be required to improve the reproduction of the salt budget in the Arctic, and, possibly, in other marginal seas. Moreover, the analysis of deep ocean characteristics simulation will require much longer numerical experiments by further increasing the computational efficiency of the model program code.

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