Bull. Nov. Comp. Center, Num. Model. in Atmosph., etc., 4 (1996), 21–29

A numerical modeling of the global ocean meridional thermohaline circulation*

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A two-dimensional, zonally averadged, latitude-depth ocean model is proposed. Numerical experiments were carried out to investigate the global process of the thermoline circulation in frames of this simple model to apply the results of investigations to three-dimensional model.

Introduction

A three-dimensional World Ocean Circulation Model (WOCM) has been developed in the Laboratory of Oceanography of the Computing Center of the Russian Academy of Sciences. It is intended for studying climate and climatic changes. The model is based on the finite element method for the spatial discretization of the primitive hydrodynamic equations combined with the splitting technique with respect to time [1, 2]. Numerical simulation of the global circulation with the use of this model was conducted in two stages. At the first stage the seasonal cycle was reproduced under assumption that salinity is constant and equal to 35‰. The model was able to reproduce the main feature of the ocean circulation and thermal structure of the World Ocean. At the second stage the space and time variability of the sea water salinity was included. We were planning to investigate the seasonal variations and the sensitivity of the thermal structure of the model ocean with respect to salinity and to obtain a more realistic picture of global circulation. After 100 years of integration we encountered some difficulties in simulation of the seasonal variability of the oceanic circulation. The enlarged heat income from the ocean surface to the deep layers was found in the middle latitudes, especially in the North Atlantic, where the maximum of salinity was present on the sea surface. This heat flux destroyed the main features of the global ocean circulation. It was obvious that the reason of this heat income to the deep layers was connected with a salinity inclusion. To study this mechanism a two-dimensional, zonally averaged, latitude-depth ocean model was constructed on the basis of the WOCM. The primary aim of this work was to investigate the global processes of the

*Supported by the Russian Foundation of Basic Research under Grant 96-05-65953 and INTAS-93-1176.

thermohaline circulation on the basis of a simple model in order to apply the results of investigations to three-dimensional modeling.

1. Equations of the model

We consider the ocean of uniform depth and angular width. The inertial terms are assumed negligible, and hydrostatic and Boussinesque approximations are made. To obtain a zonally averaged model we apply the operator

$$(\bar{\cdot}) = \frac{1}{\lambda_E - \lambda_W} \int_{\lambda_W}^{\lambda_E} \cdot \, d\lambda,$$

where λ_W, λ_E are the longitudes of the western and the eastern boundaries, to the three-dimensional numerical model(WOCM), assuming no material or diffusive flux through λ_W and λ_E.

In the differential form it will correspond to a set of zonally averaged equations written down for the sphere of radius a in the spherical coordinates (λ, θ, z)(z is directed from surface to bottom):

$$\begin{gathered}
\frac{\partial u}{\partial t} - fv = -\frac{m}{\rho_0}\frac{\Delta p}{\Delta \lambda} + \frac{\partial}{\partial z}\nu\frac{\partial u}{\partial z} + \frac{\partial}{\partial \theta}\mu\frac{n^2}{m}\frac{\partial u}{\partial \theta}, \\
\frac{\partial v}{\partial t} + fu = -\frac{n}{\rho_0}\frac{\partial p}{\partial \theta} + \frac{\partial}{\partial z}\nu\frac{\partial v}{\partial z} + \frac{\partial}{\partial \theta}\mu\frac{n^2}{m}\frac{\partial v}{\partial \theta}, \\
\frac{\partial p}{\partial z} = g\rho, \\
m\frac{\partial u}{\partial \lambda} + \frac{\partial}{\partial \theta}(v\frac{n}{m}) + \frac{\partial w}{\partial z} = 0, \\
\frac{\partial T}{\partial t} + nv\frac{\partial T}{\partial \theta} + w\frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\nu_T\frac{\partial T}{\partial z} + \frac{\partial}{\partial \theta}\mu_T\frac{n^2}{m}\frac{\partial T}{\partial \theta}, \\
\frac{\partial S}{\partial t} + nv\frac{\partial S}{\partial \theta} + w\frac{\partial S}{\partial z} = \frac{\partial}{\partial z}\nu_S\frac{\partial S}{\partial z} + \frac{\partial}{\partial \theta}\mu_S\frac{n^2}{m}\frac{\partial S}{\partial \theta}, \\
\rho = r(T, S).
\end{gathered} \tag{1}$$

Initial and boundary conditions are:

$$t = 0: \qquad u = u^0, \quad v = v^0, \quad T = T^0, \quad S = S^0;$$

at the ocean surface $z = 0$:

$$T = T_{\text{surf}}, \quad S = S_{\text{surf}},$$

$$-\frac{\nu_T}{H}\frac{\partial T}{\partial z} = Q_H, \quad -\frac{\nu_S}{H}\frac{\partial S}{\partial z} = Q_S, \quad -\rho\nu\frac{\partial \vec{U}}{\partial z} = 0, \quad w = 0;$$

at the ocean bottom $z = H$:

$$\frac{\partial T}{\partial z} = \frac{\partial S}{\partial z} = 0, \quad \nu\frac{\partial \vec{U}}{\partial z} = 0, \quad w = 0;$$

at the solid boundary G:

$$\frac{\partial T}{\partial \vec{N}} = 0, \quad \frac{\partial S}{\partial \vec{N}} = 0, \quad \vec{U}\cdot\vec{N} = 0, \quad \frac{\partial \vec{U}\cdot\vec{K}}{\partial \vec{N}} = 0,$$

where $\vec{N}$ and $\vec{K}$ are normal and tangent unit vectors to the G surface accordingly.

$$\vec{U} = (u, v),$$

u, v, w are the velocity vector components by the (λ, θ, z) coordinate directions, respectively, $n = 1/a$, $m = 1/(a\sin\theta)$, $f = -2\omega\cos\theta$, $\gamma = m\cos\theta$, ω is angular velocity of Earth rotation, p is pressure, ρ is density deviation from averaged ρ_0 =const, T is temperature, S is salinity.

To complete the model formulation we should define the zonally averaged east-west pressure gradient. We use the parameterization of Daniel G. Wright and Thomas F. Stocker [3]:

$$\frac{\Delta p}{\Delta\lambda} = -2\epsilon sc^2\frac{\partial p}{\partial s},$$

where s and c are the sine and cosine of latitude, and $\Delta p/\Delta\lambda$ and $\partial p/\partial s$ are the zonally averaged zonal and meridional pressure gradient components.

2. The numerical experiments

The domain of investigation is 5000m deep and extends from 70°S to 70°N with the closed nothern boundary according to WOCM. A roughly resolving grid $(21H \times 11V)$ was chosen. The integration started from the two different states of the resting ocean: 1) uniform temperature $T = 7$°C and salinity $S = 35‰$, and 2) climatic Levitus data, and were carried on 2000 years. The circulation was set up by thermal and haline surface forcings. The seasonal values of T and S at the surface were used to define this forcing for the global ocean circulation and the Atlantic basin.

A set of experiments was carried out to investigate the sensitivity of the ocean model to the mixed layer parameterization and various modifications of the upper boundary conditions for the temperature and salinity. As well as in WOCM, a convective mixing model was based on the integral criterion of stability [4]. The results of all the experiments, carried out with two-dimensional model, show the qualitative agreement with the three-dimensional WOCM for all types of boundary conditions and the initial fields. The structure of the global circulation obtained in the course of the numerical integration was independent of the applied initial fields. We have

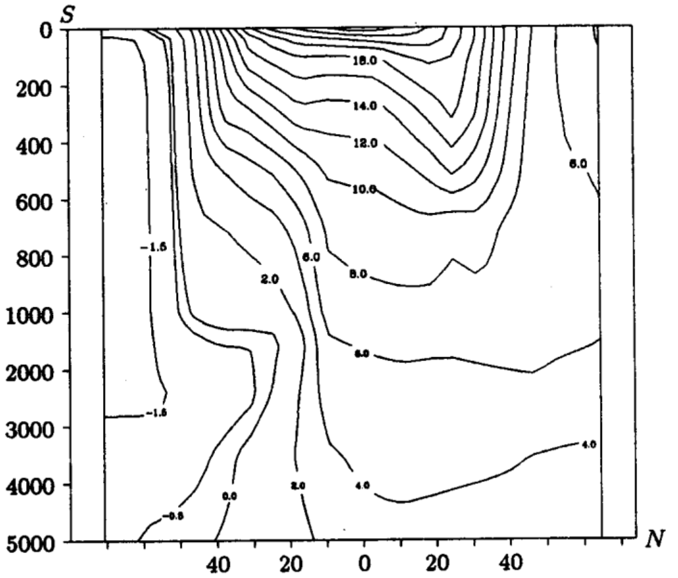

Figure 1. Temperature distribution in 2000 model years

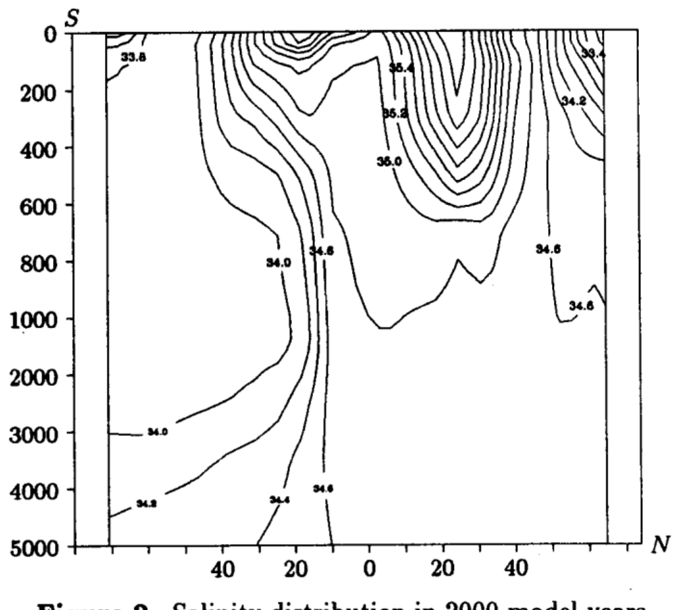

Figure 2. Salinity distribution in 2000 model years

obtained a steady circulation for constant salinity without enlarged heat flux into the deep ocean layers.

Then with salinity included, we continued the numerical integration. During the first 1000 years we saw the steady heat income through the ocean surface to the deep layers in the middle latitudes. The two-cell thermohaline circulation became unstable and was characterized by the oscillatory mode. As well as in the WOCM, the most steady heat income was detected in the middle latitudes of the North Hemisphere, when the Atlantic surface conditions with the salinity maximum were used. It seemed the surface water was spreading down to the ocean bottom. However after 1000 years the colder south polar water reached the equator and began to force out the warm water of the deep layer in the middle latitudes. As we have mentioned the cold water of the Arctic basin was excluded from modeling as in the WOCM. The warm layer in this region became shallower, but the picture of the hydrodynamic fields was unrealistic (Figures 1, 2) and the oscillatory mode of the meridional circulation still remained.

The meridional heat transport also corresponded to the WOCM result and was wrong.

The detailed analysis of the temperature and salinity fields during the time of modeling showed that these processes were caused by the heat-salinity convective mixing in winter season. The water stratification in this region is nearly neutral. So, any density fluctuations may activate the vertical mixing processes. The decrease of the surface temperature in winter season promotes the significant increase of the sea surface water density, hence the strong convective instability occurs in this period.

The main reason of the enlarged heat income is proved to be in the details of the numerical realization of the mixing process parameterization. After the time step of integration the model may form the unstable vertical distribution in the upper model layers. The mixing of these layers releases the kinetic and potential energies that may cause the mixing of the lower stable layers. With the use of the parameterizing procedure, moving from the upper level, the amount of the released energy is examined. An addition of each lower stable layer to the mixed layer results in decreasing the released energy. The aim is to find such a depth h, for which the total energy balance is zero, that is, all the energy released by the realization of the upper layer instability will contribute to the mixing of the lower layers. Assume $z_k < h < z_{k+1}$, where z_k and z_{k+1} are two subsequent vertical model layers. Then one may propose two variants for the numerical realization: mixing from the surface to the depth z_k and from the surface to the depth z_{k+1}. The latter one was earlier realized in the WOCM and reproduced in our zonally averaged model. It is the variant that leads to the enlarged heat income. The alternative variant was also tested.

We obtained a steadier picture of circulation and colder water in deep layers of the ocean for the Atlantic surface conditions after the modification of the convective model (Figure 3). However the lack of the cold water in the North of the domain did not permit us to simulate real picture of thermohaline circulation and heat transport for the Atlantic (Figure 4). Within the frame work of 3-dimensional model it corresponds to the necessity of the inclusion of the North Arctic Ocean into the integration.

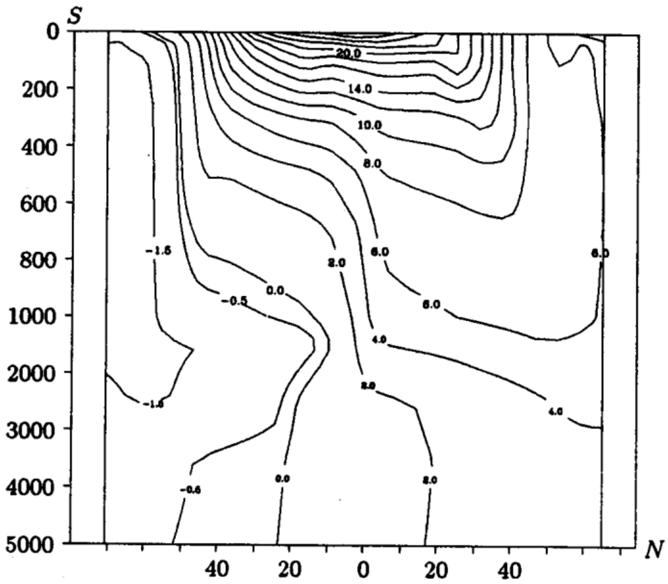

Figure 3. Temperature after model modification (t = 2000 years)

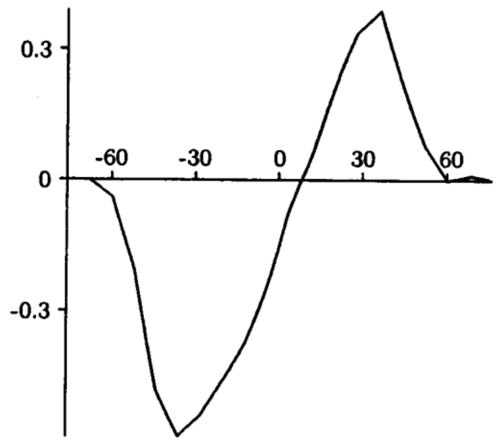

Figure 4. Transport of heat (Pw)

The last experiments were started from a state of rest with the annual restoring surface temperature and salinity absolutely symmetrical to the equator and with the seasonal surface conditions identical for every hemisphere. The model was integrated for 20000 years. The picture of the annual circulation was identical in both cases. Figures 5–8 show the temperature and the salinity fields, the steady annual streamfunction of the meridional mass transport and the meridional heat flux, all being symmetrical to the equator.

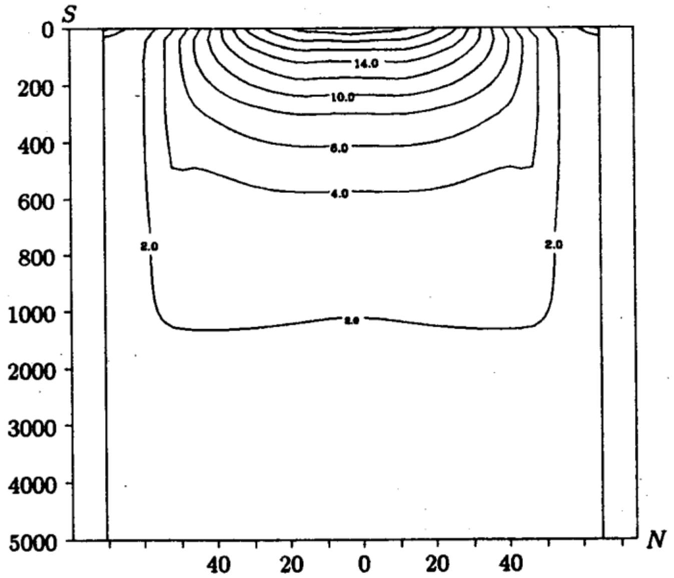

Figure 5. Global temperature distribution (t = 20000 years)

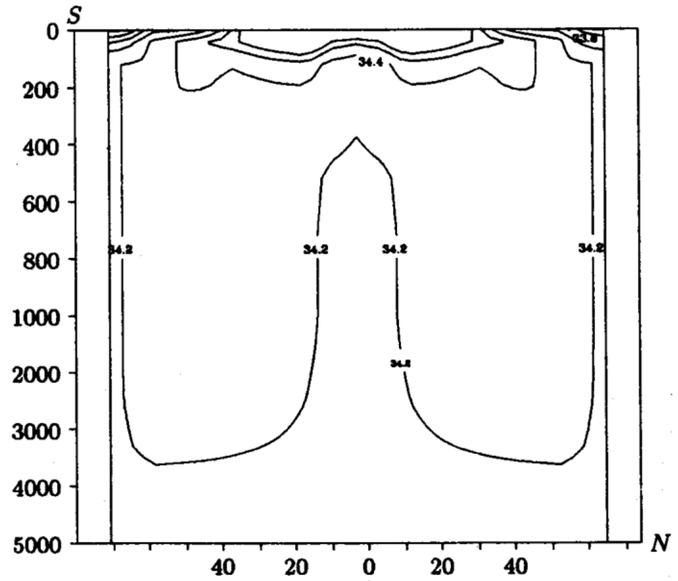

Figure 6. Global salinity distribution (t = 20000 years)

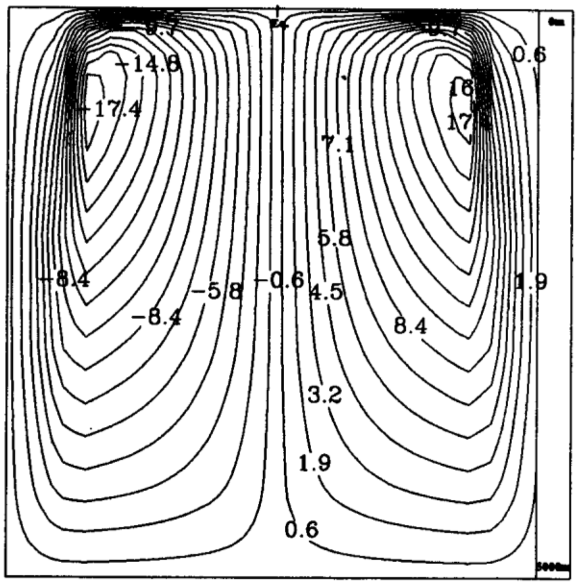

Figure 7. Overturning streamfunction ($t = 20000$ years)

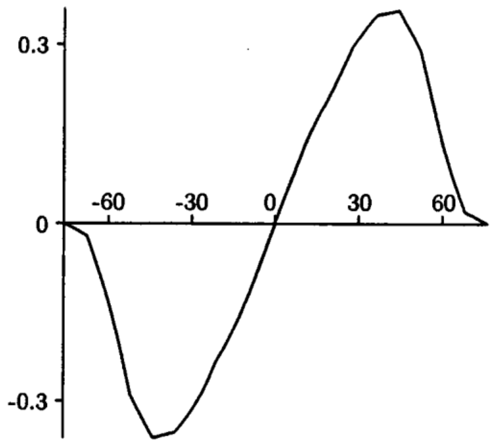

Figure 8. Global meridional transport of heat ($t = 20000$ years)

The quality of the simulation using 3-dimensional model is expected to be improved by including the new modification of the convective model.

An important aspect of the present study is the construction of the zonally averaged model of the meridional oceanic circulation which, as the obtained results indicate, may be a useful tool for testing the three-dimensional model as well as for the study of a number of problems of the global water circulation and the north-south heat transport modeling.

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