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Simulation of the global ocean response to warming and cooling the surface waters at century scale*

A.V. Scherbakov, V.V. Malakhova

A three-dimensional large-scale geostrophic model of climate of the World Ocean with realistic topography is presented. The experiments on the response of the model on variations of the ocean surface temperature were carried out: warming by 1.5 degrees during 50 years, cooling by 1.5 degrees during 50 years, and warming–cooling together with the same amplitude. It has appeared that the global ocean model stronger and longer responses to cooling than to warming.

Data about the paleoclimate [1] show that the climatic variations have a periodic nature. Warmings are replaced by coolings, and the periods of these fluctuations are varying from tens up to thousands years. In this paper, an attempt is made to simulate the response of the World Ocean to the variability of the surface waters temperature at the century scale.

In our previous works [2–4], a detailed description of the used here quasi-geostrophic numerical model of the World Ocean climate was given. The model is based on solution of the three-dimensional equations of heat and salt transport on the regular five-degree latitude-longitude grid and on the irregular one, condensed to the surface grid in vertical. On the horizontal coordinate, the conservative nine-point difference scheme of the second order of approximation based on Richardson's extrapolation [5] is applied, on the vertical coordinate – the second upwind scheme of the first order approximation is exploited, [6].

In [3], it was shown that the increase of resolution along the vertical coordinate for the coefficient of the vertical eddy diffusion of heat and salt of 0.2 cm^2/s results in a more real mean temperature of the World Ocean. With an increase of resolution in vertical from 12 up to 24 and 36 levels, the mean temperature decreases, respectively, from 4.2 up to 3.9 and 3.8 grades. This occurs due to decreasing the scheme viscosity. If one takes into account the fact that according to the observations data the mean temperature of the World Ocean is 3.62 grades, [7], it is possible to conclude that at increasing a resolution, the convergence of the mean simulated temperature of the World Ocean to its true value takes place. However at further increasing a resolu-

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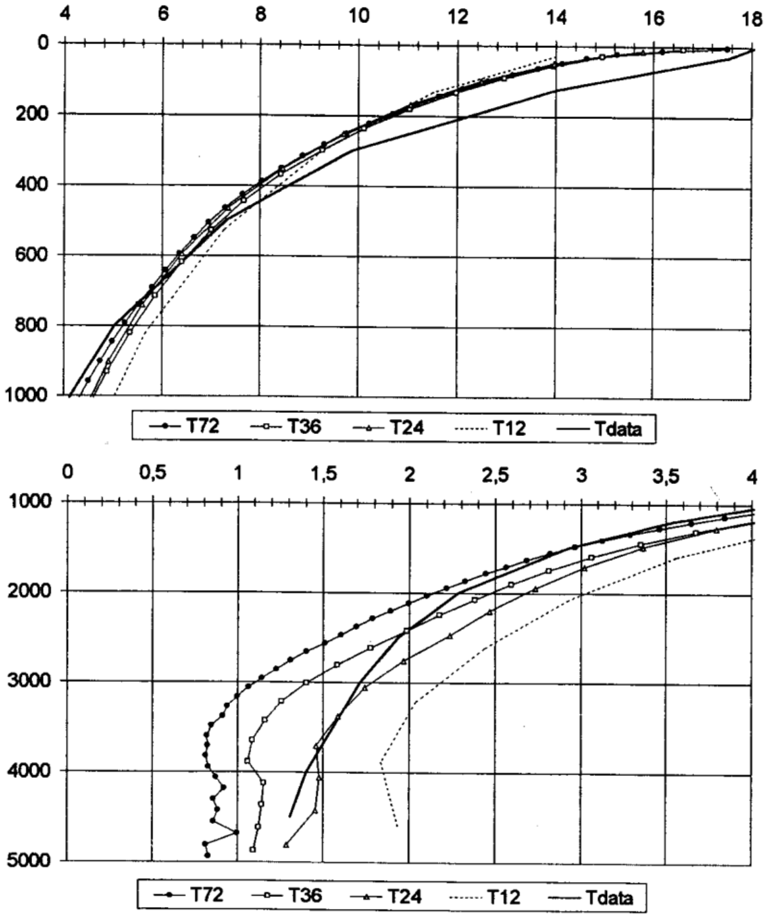

Figure 1. Mean vertical profiles of the temperature in the model of the ocean with 12, 24, 36, and 72 levels in a layer from 0 up to 1000 m (the upper panel) and in a layer from 1000 up to 5000 m (the lower panel)

tion in vertical up to 72 levels, the mean temperature of the ocean becomes equal to 3.5 grades, which is already less than the true values, and indicates to a very small value of the eddy diffusion coefficients of heat and salt.

Possibly, this is also supported by the vertical mean profiles of heat of different resolutions which are shown in Figure 1. In a high layer up to 400–500 m, the simulated field of heat for all the variants of resolution appears colder as compared to observations. The effect of improving the resolution is especially distinct for the first level of each grid. At increasing the resolution from 12 to 24, 36, and 72 levels, the difference with the observational data from 4.1 grades up to 2.3, 1.3, and 0.6 grades, respectively, decreases.

In a layer from 100 up to 1000 m, the difference between solutions on all grids appears inessential. For the deep ocean, the decrease of the scheme viscosity appears to be more significant. The increasing resolution gives a less smoother curve, as a result, the value of temperature on the last calculation level with an increase in resolution varies from warmer to colder values as compared to observed data. In this layer, in the models with 12 and 24 levels, water appears warmer, than expected, and at 36 and 72 levels – colder.

The mean vertical profiles of salinity at increasing the resolution from 12 up to 24 and 36 levels are closer to the observational data, though insignificantly in the deep ocean. And the increase of resolution up to 72 levels gives insignificant improvement only in the upper layer, and there is no improvement deeper than 1000 m. The reason explaining this fact, as shown in [4], is the absence in the model of parameterization of the highsaline Mediterranean waters.

Therefore, further experiments on analysis of the response of the model of the World Ocean climate to varying the surface temperature of the ocean of the century scale were conducted with allowance for parameterizations of the highsaline Mediterranean waters, [4]. Three experiments on the grid with resolution of 24 levels in vertical were carried out. All the experiments start with an identical climatic state, which was obtained as a result of the long integration up to the quasi-stable state with time about 5000 years, [4].

In the experiment "Warming", the seasonally changing surface temperature of the ocean at each point of the latitude–longitude grid, except for the areas covered with ice, annually increases by 0.03 of grade within 50 years, and then, also by 0.03 grade decreases to the initial values within 50 years.

In the experiment "Cooling", similarly, the surface temperature at first is decreased by 0.03 grade annually within 50 years, and then, also, by 0.03 grade it was increased up to the initial values within 50 years.

In the experiment "Warming–Cooling", at first the surface temperature is increased by 0.03 grade annually within 50 years, and then within 100 years, also by 0.03 grade it is decreased, and, at last, during the following 50 years it is increased up to the initial values. Thus, this experiment combined together the two previous ones.

The variation of the mean temperature of the World Ocean for all the three experiments is shown in Figure 2. In the experiments "Warming" and "Warming–Cooling", the mean temperature of the ocean is changed in the same manner in the first 100 years due to the identity of experiments up to this moment. After the end of heating of the surface waters in 50 years, the mean temperature was increased by 0.2 grades, and it was still growing slowly within 10–20 years reaching a maximum value. Further, in the experiment "Warming" during 50 years of cooling of the surface waters, the mean temperature is slowly decreasing and continues to decrease further within 100 years, and after termination of cooling of the surface waters up to the values less than the initial, and only then it grows very slowly up to the original values.

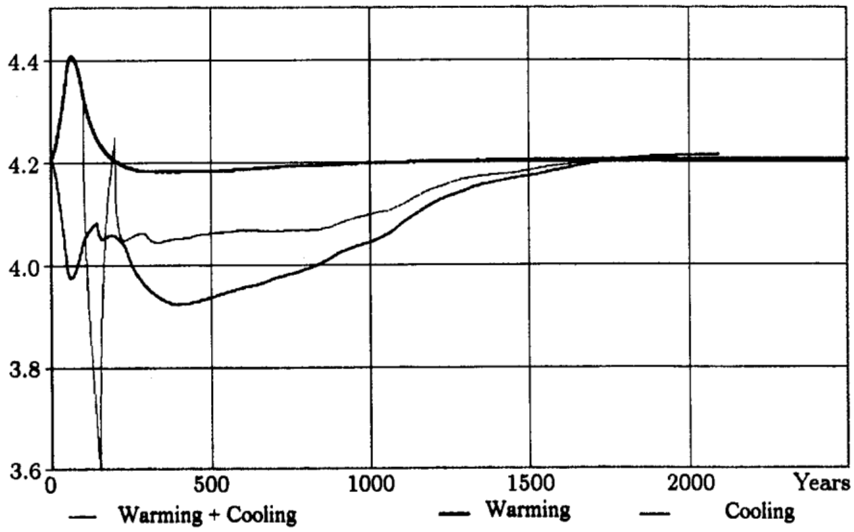

Figure 2. The time series of the global average temperature for the experiments "Warming", "Warming+cooling", and "Colling"

The mean temperature of the ocean in experiment "Cooling" behaves in a more complex way, at the beginning of cooling of the surface waters it slowly decreases approximately by 0.2 grades, after the end of cooling the mean temperature continues slowly to decrease during 10–20 years, though the surface waters have already begun to get warm. Then the mean temperature increases along with an increase of the surface temperature and continues to increase 40 years more after the surface water temperatures have achieved the original values. Further, after a short period of a few years of cooling and the ten year increase, the long-term decrease of the mean temperature within 200 years begins. And only after that the mean temperature of the ocean starts to increase and after 1600 years becomes close to the original values.

Thus, the model of the ocean responses to warming of the surface water by a short-term increase of the mean temperature by 0.2 grades, and further in the period of about 300–500 years practically achieves the original state. The response of the model of the ocean to cooling lasts more than 1600 years, and the recovery is much more slow. Probably it is connected with conditions of both experiments and the mechanism of penetration of a thermal signal into the deep ocean. The basic process of penetration of a thermal signal into the deep ocean in the model is the convective mixing. The universal warming of the surface waters does not preclude with fall-winter convective mixing. The convection, as well as earlier, takes place in high latitudes of all the oceans and transports the warmer water in deep layers of the ocean, Figure 3. A similar result is obtained in work [8], where an increase of the

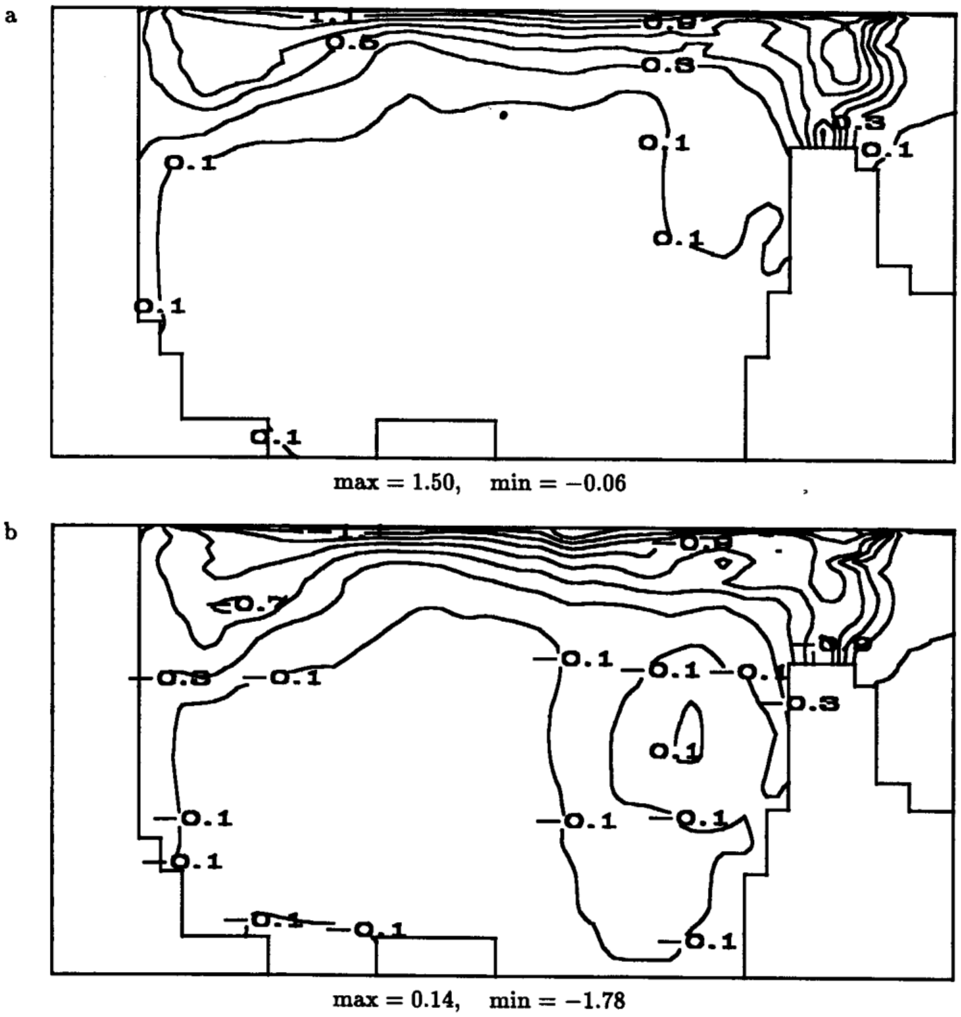

Figure 3. Zonally mean deviations of heat in 50 years for a) "Warming" and b) "Cooling"

atmosphere temperature in the restoring boundary conditions by 2.9 grades for 50 years was supposed.

The general cooling of the surface waters not only intensifies the process of forming an unstable stratification, but also increases their spatial extension towards subtropics. On a meridional plane, Figure 3, the zonally mean deviations of heat in 50 years for "Warming" and "Cooling" are qualitatively similar, differing only in the sign of the anomaly, however cooling is penetrating deeper in the northern hemisphere, practically, up to the bottom.

In Figure 4, the same deviations in 200 years of the experiment for all the three versions are shown. Here already all the fields are qualitatively

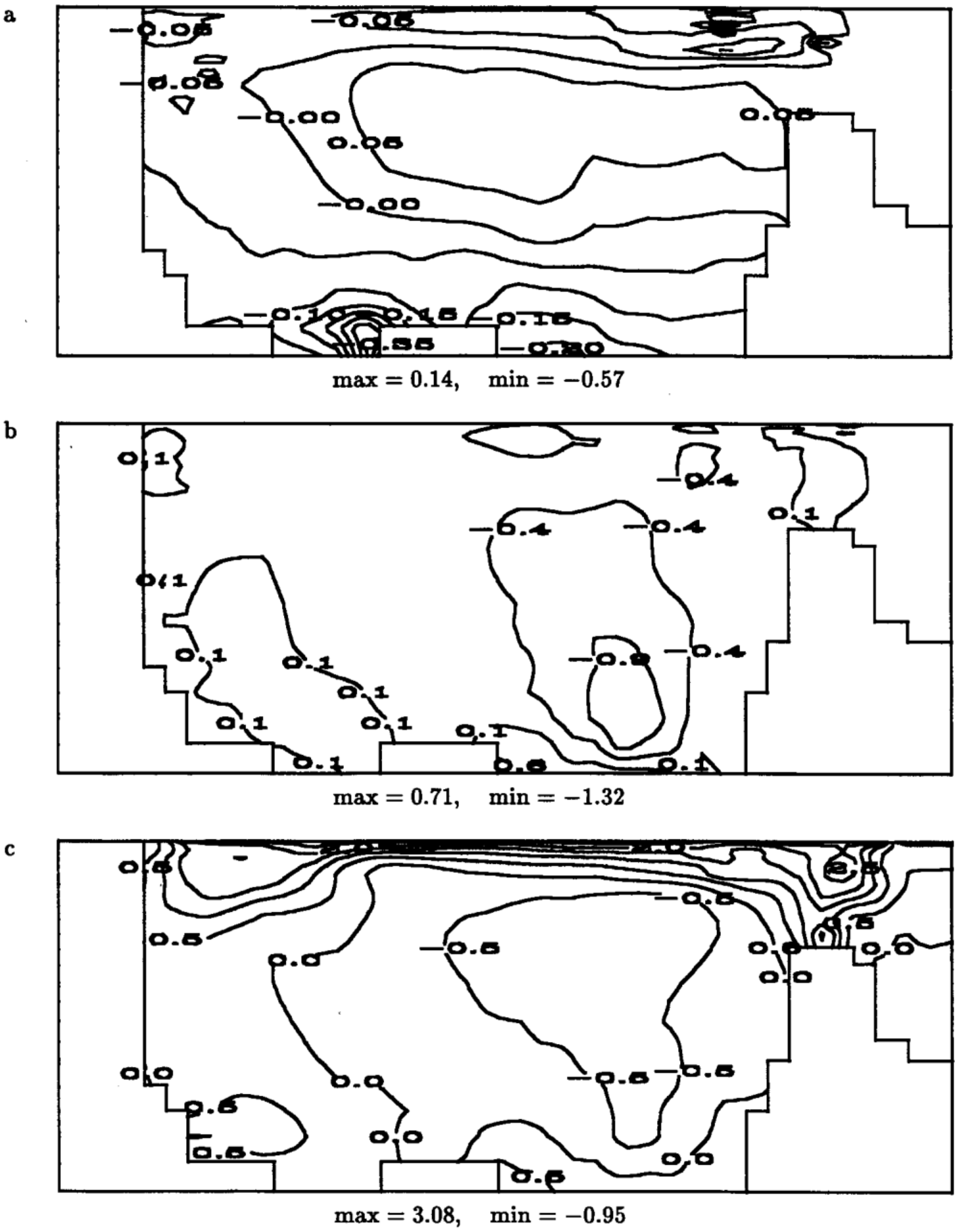

Figure 4. The zonal mean deviations of heat in 200 years for the experiments a) "Warming", b) "Colling", and c) "Warming+cooling"

different. If in the variant "Warming", the positive anomaly of heat was diminished till 0.05 grade, in the version "Cooling" practically all the ocean is covered with warmer or colder anomalies, with a negative extremum of -1.2 grades for the bottom in the northern hemisphere. And, it is seen, that in the experiment "Cooling", the ocean is heating in the high-latitude areas of forming the bottom waters.

Thus, it is possible to conclude that the model of the ocean stronger and longer reacts to cooling, than to warming.

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