Experiments with the Global High-Resolution Model MPI ESM and Several Estimations of its Stability to the Initial Perturbation

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Abstract. The studies used the high-resolution MPI-ESM model developed at the Max Planck Institute for Meteorology (Hamburg, Germany). The simulation results of this model have been performed and analyzed on the supercomputer Lomonosov-2 of Lomonosov Moscow State University. In the experiments, an ensemble of different initial data was created and the model was integrated for different periods, starting with this data. To analyze the results, different statistical methods have been used, as well as author's estimates based on ensemble experiments. We studied the extreme characteristics of ocean level, surface temperature, ice cover and several others over a period of 30 years. Their statistical distribution was constructed, the parameters of this distribution were found out and the statistical forecast was studied. It is shown that the statistical forecast of the level and surface temperature corresponds to the calculated forecast obtained by the model. The localization of extreme level values was studied and an analysis of these results was carried out. Based on the results of studies, estimates are made for the behavior of complex nonlinear models, sensitivity to initial disturbances, and analysis of the behavior of these disturbances. It is shown that the behavior of such nonlinear systems is quantitatively described by the statistical characteristics of the simulation results. A method is also proposed for analyzing the asymptotic behavior of these characteristics with a long integration time.

Keywords: Nonlinear circulation models, Numerical Ensemble Experiments, Stability Analysis of the Model Trajectories.

1 Introduction

Numerical ensemble experiments with complex nonlinear models are one of the most common methods for studying model trajectories, their behavior in time and space, and also studying the conditions of their stability for a sufficiently long integration period. It is important to note that these experiments require the use of a large amount of computing power, computer time and memory, solving problems of visualizing the results, and many related problems. In recent years, thanks to significant progress in the field of computing power and numerical modeling, systems for the data storage and processing, such ensemble experiments become available for many research groups and individual users belonging to a particular scientific community. This, in turn, contributes to the further development of numerical modeling, the ability to analyze model data, the results obtained with subsequent comparison. Today, there is a lot of research work with modern models. The work on numerical climate modeling is carried out by various international groups, for example, the GFDL [1], NEMO [2], Max Planck MPI-ESM [3] models and others. Among the Russian developments, the most well-known in this area are the Marchuk INM of RAS, for example, [5, 6]. Many results recognized by the scientific community are presented in the IPCC Bulletin [7], which gives an analysis of physical characteristics and the environment based on model results. The scientific interest in climate modeling and numerical models is caused not only by their practical significance, but also by the fact that these models significantly enrich studies in the field of nonlinear systems of differential equations and contribute to understanding the nature of the simulated processes. In particular, the problem of stability and sensitivity of the model to initial perturbations is very interesting and requires serious analysis. As applied to our problem, it should be noted that the system of equations is rather complicated, and analytical methods do not work, except for a few simple cases. In order to obtain sufficiently substantiated results, it is necessary to provide a number of computational experiments and conduct an in-depth analysis of the results. Some works in this direction are presented in [8]. However, this research area is so vast that, although climate modeling began in the mid-20th century, when the first capabilities and resources of computers appeared, it cannot be argued that there are currently no directions for fundamental analysis.

In this paper, we study the behavior of the main physical characteristics for a certain time period of integration using the high-resolution MPI-ESM model mentioned above [3]. In contrast to the low-resolution model used earlier [9], a number of new and interesting results that were previously irreproducible can be obtained on this model. In the experiments, a set of initial data was selected, consisting of 50 different fields, and model characteristics were observed for 10 or more years of integration with these data. It is known that model equations lead to a scatter of calculation results due to the initial perturbation. By analyzing this scatter, we can evaluate the stability of the model in order to evaluate its statistical and analytical properties and draw a conclusion about its physical and mathematical features. The main goal of the work is to analyze the results of modeling with a high-resolution model, statistical estimates of the stability of this model to perturbation of the initial data and comparison of model results, in particular model fields and their spatial-temporal variability with field observations and known trends in climate change. Some results are presented in sections of the article.

2 Model, Spin-Up, Experiments and Data

2.1 Model Description

A detailed description of the model used is contained in [3]. In this context, it is important to show the features of the selected configuration and its comparison with the version of the model used earlier.

For the MPI-ESM-HR version, the atmospheric model ECHAM6.3 was used in conjunction with the MPIOM ocean model, version 1.6.2. The physics of the ECHAM model is presented on a regular Gaussian grid horizontally and at 95 vertical levels, with a relatively high resolution stratosphere and a "rigid lid" model at 0.01 GPa. The MPIOM oceanic component is configured on a three-pole grid with a nominal horizontal resolution of 0.4° on a quasi-isotropic grid north of the equator. In the vertical plane, 40 unevenly spaced levels are used. The first 20 levels are distributed from the surface to a depth of 700 m. Topography of the bottom is described using a partial step [10]. The physics of the MPIOM model is the same as in the previously used version of the CMIP5 model and its detailed description can also be found in [3]. Ocean and atmospheric components of the model are connected by the OASIS, -Atmosphere-Ice-Ocean block. The model also has blocks of carbon cycle change and a number of other blocks that are not described in this context. In our work, the initial data was changed only for the MPIOM module, although the model was fully integrated.

2.2 Tuning and Spin-up

Tuning up the model is a special and difficult task. In this work, ready-made fields for restarts were taken from the so-called overclocking experiments Spin-Up performed in [11]. A series of ensemble experiments were conducted with various scenarios. In particular, the calculations were carried out as follows: starting from 50 different initial conditions from the IPCC database [7] (Intergovernmental Panel on Climate Change, IPCC, English Intergovernmental Panel on Climate Change, IPCC), the model was integrated sequentially for 10 and more years. After integration, 50 different model fields obtained were recorded and analyzed. The averages were calculated before and after integration and anomalies with respect to these averages.

3 Results of Experiments and their Analysis

As a result of the conducted experiments the obtained fields of the model characteristics have been analyzed and plotted. Several fields such as sea level field, temperature field and ice coverage in the Polar Ocean are presented below.

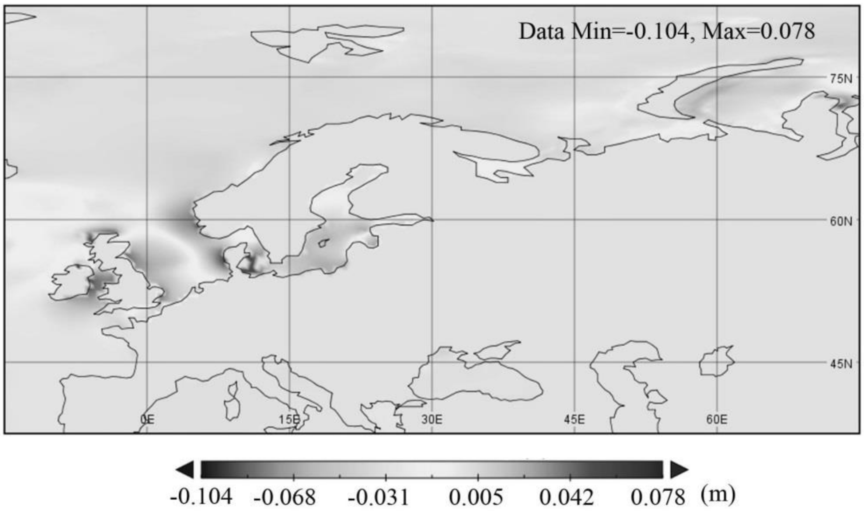

Fig. 1. The model prediction of the sea level variability (m) in the Russian Arctic Zone for 2000-2027 year (January). High resolution model (MPI-ESM-HR).

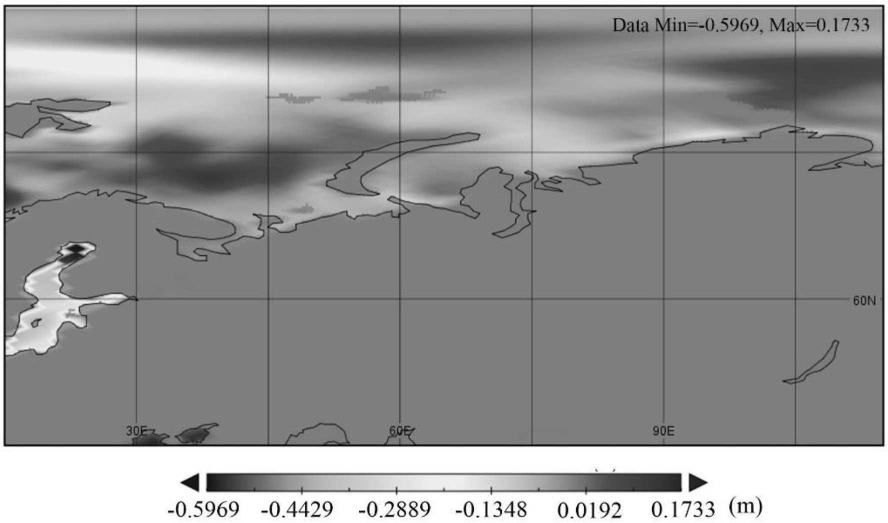

Fig. 2. Sea level variability (difference) for January 1965-2016. Low resolution model (MPI-ESM-LR) in the Russian Arctic Zone.

Figure 1 shows the difference in the level fields for different model years for the Russian Arctic zone. In Fig. 1 a forecast is made from 2000 to 2027 (27 years) and in Fig. 2 – analysis over 50 years from 1965 to 2016. In Fig. 2, the climatic tendency of warming in the Arctic is clearly visible – the model level increased to 0.17 m almost everywhere, except for certain areas in the Baltic Sea and north of Canada, where it slightly decreased. Figure 1 shows, in a high-resolution model, more detailed the areas of further rise and fall of the level – northeast of Novaya Zemlya, off the coast of Great Britain and Norway. There, however, the values of this rise are about 3-4 cm, so there is no need to talk about a noticeable trend. On a rough model, the entire Baltic Sea has a downward trend, and on a more detailed model, details are visible - part of the sea has a tendency to increase, part - an inverse trend. In general, the model results coincide with those observations made by the IPCC.

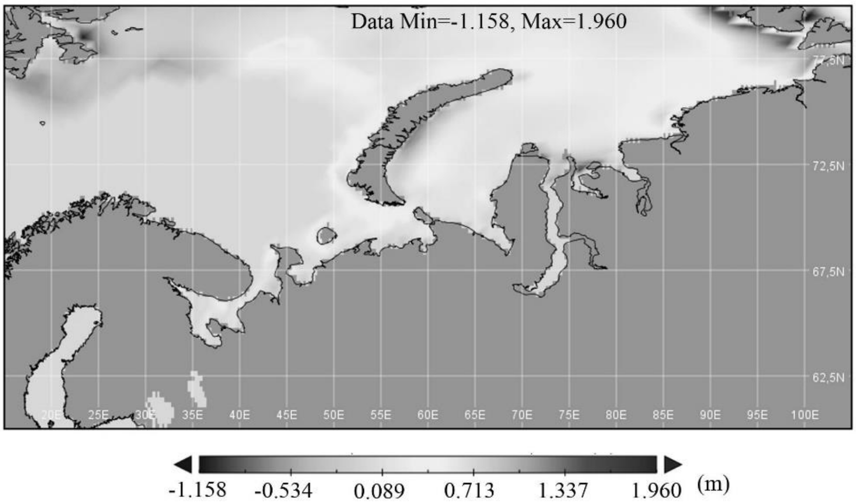

Fig. 3. The difference of the ice fraction in the for Russian Arctic Zone 2000–2027 (model prediction) model MPI-ESM-HR.

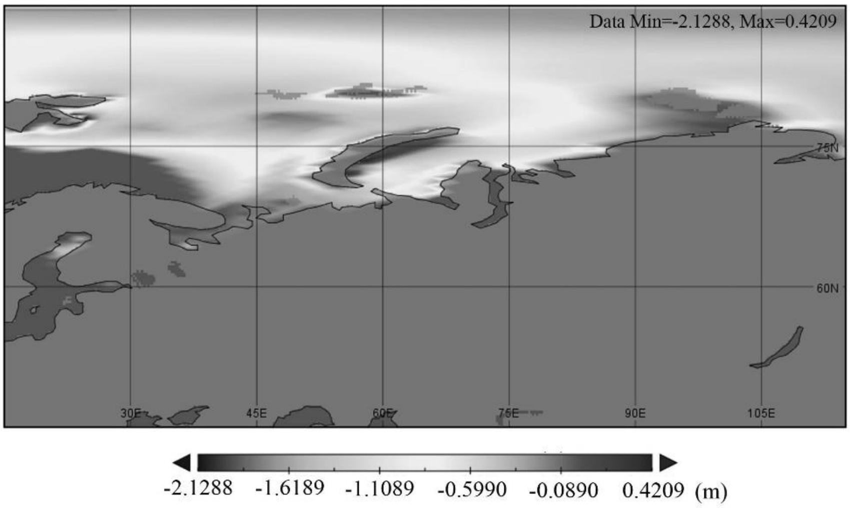

Fig. 4. The difference of ice fraction for 1965 and 2016 (January) for low resolution MPI-ESM-LR. Russian Arctic Zone.

Figs. 3 and 4 demonstrate the tendencies in ice fraction for 2 different time-periods. Fig. 3 shows the model prediction on 2027 started from 2000 and Fig. 4 shows the difference between 1965-2016 for low resolution model. It is clearly visible the tendency to the ice thickness everywhere in Arctic except some zones in the East of Russia and to the eastward from Novaya Zemlya. The low resolution model shows the global fall of ice thickness during 40-year period everywhere except Severnaya Zemlya archipelago. Some questions arise the slight increase of the ice thickness in Baltic Sea but this can be explained because the increase is not significant, it is about 30 cm and this is really observed in January.

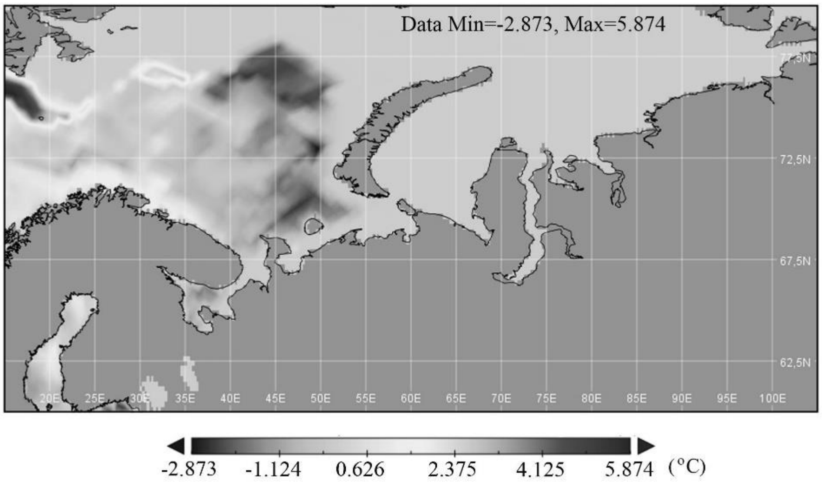

Fig. 5. Potential temperature difference in Russian Arctic zone 2000-2027. Model MPI-ESM-HR.

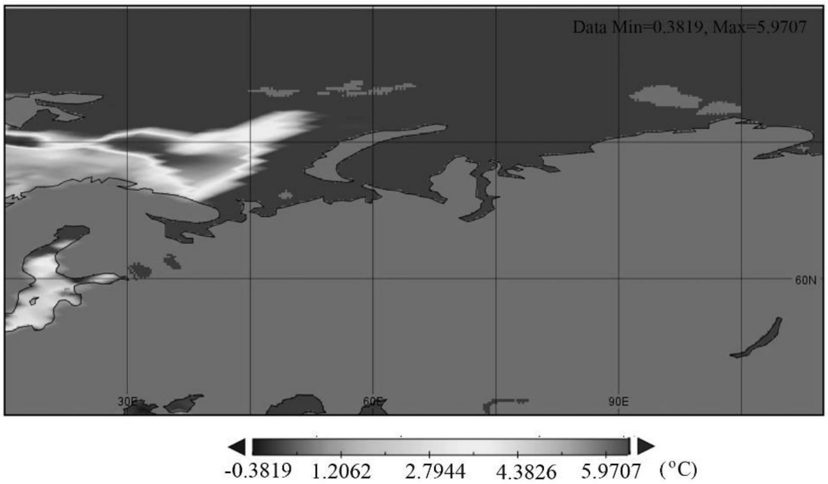

Fig. 6. Potential temperature difference 1965-2016. Model MPI-ESM LR.

The last group of figures refers to the difference in sea surface temperature (SST) for these two versions of the model. Fig. 5 produces a forecast for 2027 and a notice-able positive difference is visible in the Svalbard area, and a relatively small positive difference is in the main part of the Russian Arctic. The cooling is visible in the area north of Scandinavia and east of Novaya Zemlya. In the rough model, the temperature rises, and a noticeable one is visible everywhere, which confirms the natural tendency to global warming for 1965-2016.

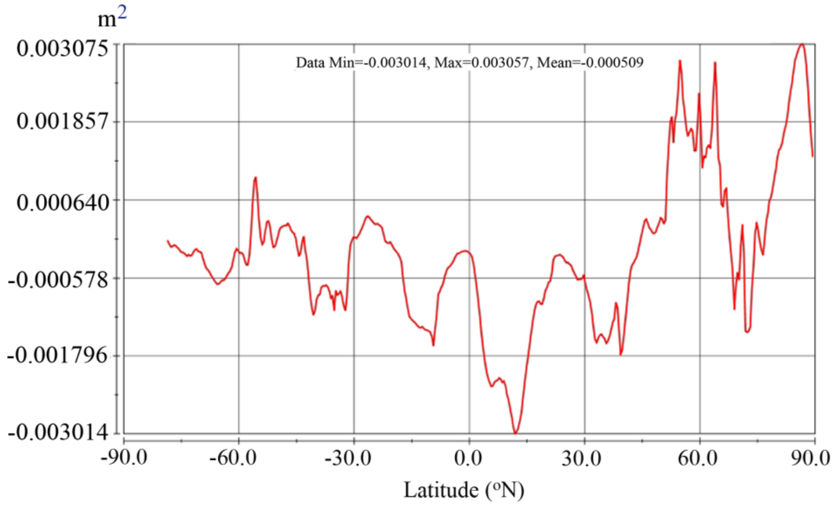

Fig. 7. The variance of the ocean level before and after integration for a period of 10 years.

In Fig. 7 shows the behavior of the difference in the dispersion of fields before and after integration, averaged over latitudinal circles (i.e., longitude). It can be seen that over 10 years of integration, randomness significantly increases, that is, the value of deviations from the middle fields, which is mainly concentrated in the northern latitudes. The magnitudes of this randomness are small, but not negligible, their inclusion in understanding global processes is essential. These quantities are also associated with external influences, which are caused by a number of reasons, primarily greenhouse gases and other factors, apparently of anthropogenic.

4 Conclusions and Outlook

The results obtained from the physical point of view can be interpreted as follows. The carried out numerical experiments confirm the tendency for a global increase in temperature, which corresponds to the real observations and conclusions of the IPCC. This process is inhomogeneous. At high latitudes, heating is noticeably more intense than the global average. As a result of this increase in temperature, ice melting and other climatic processes occur, which are actively discussed both in the scientific community and in the press. In our studies, such processes are not shown, but they are known from a number of sources [13] and the IPCC [14] and WMO [15] reports

(World Meteorological Organization, WMO, World meteorological organization, WMO) and other studies with this model, [16].

We also note that the fact of an increase in variances characterizes an increase in randomness in the behavior of natural processes. In particular, this can be seen in the increase in anomalously cold and abnormally hot seasonal temperatures in different parts of the planet. There is an increase in rainfall, the appearance of abnormally strong winds, sand storms in uncharacteristic areas and in uncharacteristic seasons.

The reflection of the listed phenomena in the results of numerical modeling is a consequence of the nonlinearity of the joint ocean – earth – atmosphere model under consideration. From this nonlinearity, for example, it follows that the average values of the characteristics during ensemble modeling do not coincide with the average values of the model itself, which is a special object of research.

Investigations of such nonlinear models are needed not only from the point of view of studying systems of nonlinear equations, but also for understanding natural processes.

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