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Simulation of the modern climate using the INM-CM48 climate model

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Abstract: We consider simulation of the present day climate with the use of the climate model INM-CM48 in comparison with the result of the previous model INMCM4.0 which used different parameterizations of many physical processes and also in comparison with the model INM-CM5 which uses the same parameterizations, but with better spatial resolution. It is shown that the model INM-CM48 reproduces the modern climate better than the model INMCM4.0 in most indicators.

Keywords: Climate, model, precipitation, temperature, precipitation error, parameterization.

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Dedicated to the 80th anniversary of Prof. Valentin P. Dymnikov

The development of climate models and numerical experiments with them is one of the main directions of modern research of climate and its changes. The construction of climate models in INM RAS (Institute of Numerical Mathematics of the Russian Academy of Sciences) began with the work by Marchuk et al. [7], the next version of the joint model INMCM3 of general circulation of the atmosphere and ocean and the results of climate change modelling for 19th-22nd centuries calculated with the help of this model in the framework of CMIP3 program (Coupled Model Intercomparison Project, Phase 3) were presented in [10]. A version of the INMCM4.0 model and the results of climate change modelling within the framework of CMIP5 program were presented in [11]. Now there is a need to conduct numerical experiments simultaneously with several versions of the climate model differing primarily in their spatial resolution. For example, the stratosphere dynamics and its influence on the troposphere are well reproduced in the model INM-CM5 [13], but such model requires several hundred processors for the efficient computation on a supercomputer with distributed memory. For some calculations, for example, for modelling paleoclimate where long-term experiments are required and a good reproduction of the stratosphere is not a priority, it is better to have a model with a lower upper boundary, but which is close to the INM-CM5 model in physical nature. Exactly such a model is described in this paper.

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1 Model and numerical experiment

The INM-CM48 climate model has the same resolution in the atmospheric block as the previous version of INMCM4.0, i.e., the mesh sizes for longitude and latitude are 2 and 1.5 degrees, respectively, 21 vertical σ-levels up to values 0.01 (about 30 km) are used. The equations of the atmosphere dynamics are solved by finite-difference methods. The parameterizations of physical processes correspond to the INM-CM5 model. This model contains an aerosol block [12], takes into account the direct impact of aerosols on radiation, and also the first indirect effect (the influence of aerosols on the condensation rate). The difference between the parameterizations used in the INM-CM48 model and those included in the INMCM4.0 model consists in the following. The INM-CM48 model has an aerosol block where the concentration of 10 types of aerosol and their radiative properties are calculated interactively, and in the model INMCM4.0 the aerosol distribution and its properties have been prescribed. In addition, in the INMCM4.0 model the large-scale condensation is triggered only when the humidity in a cell exceeds the saturated value, and the fraction of the cell occupied by clouds and the water content of clouds were calculated independently of condensation and diagnostically. In the INM-CM48 model, the fraction of a cell occupied by clouds and the water content of clouds are prognostic variables whose evolution takes place according to [9].

In the ocean block, the resolution of the INM-CM48 model is 1×0.5 degrees in longitude and latitude, as in the previous version INMCM4.0. The main differences between ocean blocks are the following. In the INM-CM48 model, implicit schemes for solving the transfer equation are replaced by explicit ones to improve parallel properties of the computational code. The dependence of the background vertical diffusion coefficient on depth is introduced in the case of its increase below 1000 m for more correct description of depth profiles of the temperature and salinity.

Historical runs were performed with the INM-CM48 model for the period from 1850 to 2014. To do that, the concentration of greenhouse gases, emission of anthropogenic aerosols, concentration of volcanic aerosol, solar constant and solar radiation distribution over the spectrum were specified according to the evaluations from observations over these years relative to the CMIP6 protocol [3]. Simulation data for 1979–2014 were used to analyze the average climatic state. For comparison of temperature, pressure, and wind speed climate parameters we used the ERA-Interim reanalysis data for the same years [4], the precipitation data of GPCP [1], and ocean state data [2].

2 Results

We consider the simulation of the mean-climatic state by the INM-CM48 model. The most important parameter characterizing the climate model is the surface air temperature. The error of the surface air temperature is shown in Figure. 1. In most tropical and subtropical regions the mean annual temperature error does not exceed 2 degrees. The exception is the subtropics of North Atlantic and North Pacific Ocean where the temperature is lowered by 2–4 degrees. This underestimation is most essential in summer months. Compared to the reanalysis data, the temperature is also underestimated in the Arctic and Antarctic, and it is overestimated at moderate latitudes of the southern oceans. The INMCM4.0 model underestimates the temperature by 2–8 degrees in the southern half of Eurasia, in most parts of Africa, in the tropics and subtropics of North and South America. In the INM-CM48 model this error is fixed or greatly reduced. The temperature error in the INM-CM48 model is very similar to that of the INM-CM5 model, but in some places the error of the INM-CM48 model is slightly greater in value. Namely, the temperature is more overestimated in the southern ocean and in places of separation from the coast for the Kuroshio and Gulf stream. The average annual temperature error norm (standard deviation) is 2.48K for the INM-CM4.0 model, 2.06K for the INM-CM48 model, and 1.87K for the INM-CM5 model.

The precipitation error for the INM-CM48 model is close to the error of the INM-CM5 model shown in Fig. 2 in [13]. The mean annual precipitation is overestimated over the tropical Indian ocean, Indonesia, and along the Southeast coast of Asia (mainly due to winter). Over the Pacific Ocean, the amount of precipitation

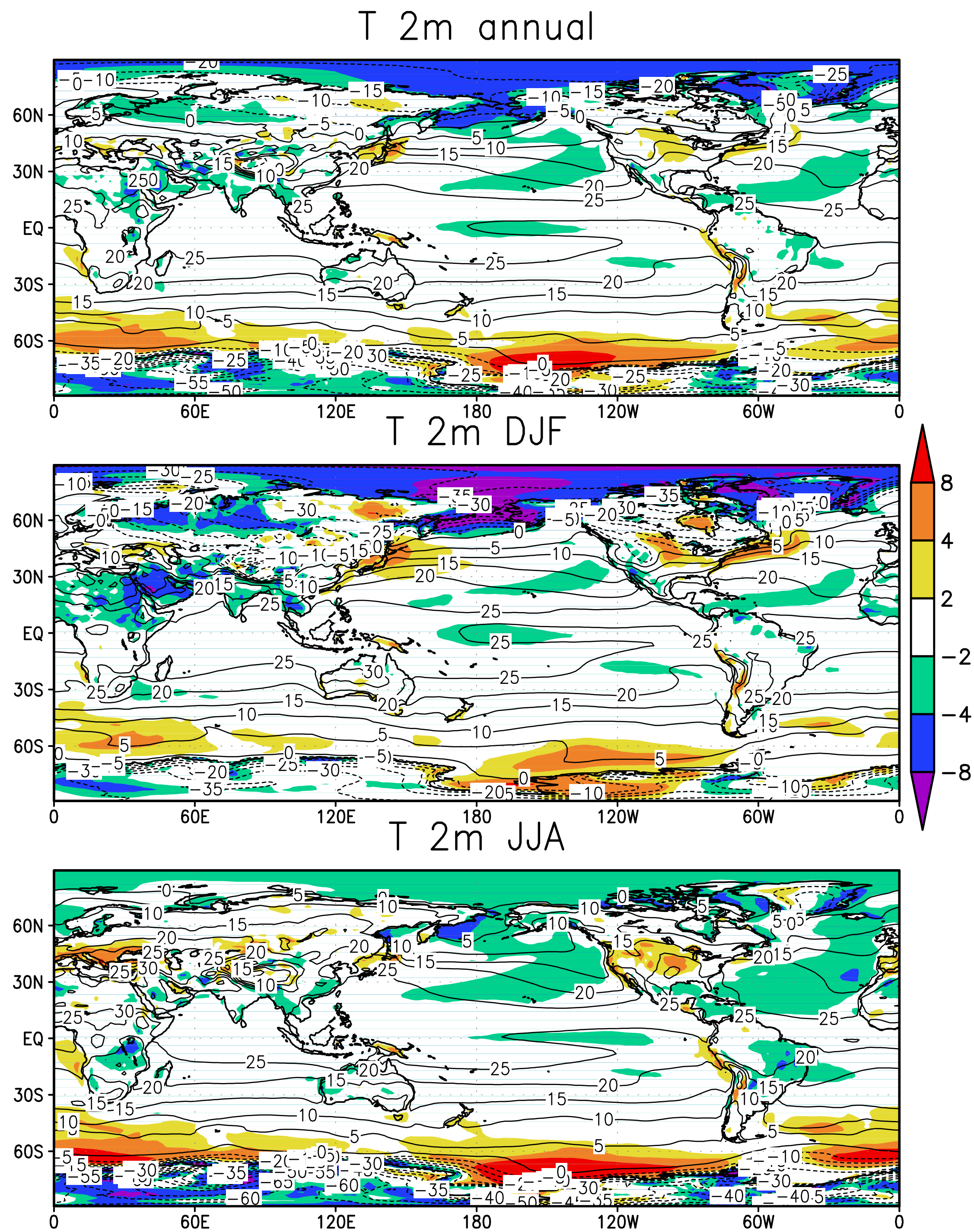

Fig. 1: Air temperature difference (K) of the 2nd level according to the data of INM-CM48 model and ERA-Interim reanalysis; annual mean (above), in December–February (middle), in June–August (below). The color indicates the difference, isolines correspond to the temperature according to model data.

is underestimated directly near the equator, and on the North and South branches of ICZ it is overestimated. The overestimation of precipitation in the southern ICZ branch in the Pacific Ocean, in tropical Indian ocean, as well as the overestimation of precipitation in the Atlantic Ocean near the equator and just to South, and the underestimation of precipitation to the North of the equator are common errors of modern climate models. In the INMCM4.0 model, these errors had even greater value, the norm of the simulation error for mean annual precipitation was 1.61 mm/day for this model, for the INM-CM48 model this value was 1.39 mm/day. The norm of the error for the INM-CM50 model was 1.36 mm/day. In addition to errors in the tropics, which have a greater magnitude in absolute units, all versions of the model inherent an error being characteristic for most modern climate models related to underestimation of summer precipitation in southern Europe.

The pressure at the sea level is also one of the most important weather fields, which simulation shows in many respects the quality of modelling the atmosphere dynamics as a whole. In winter, the Icelandic minimum and Siberian anticyclone are reproduced well by the model, and the Aleutian minimum is shifted to the North-East relative to the observed one. In summer in the Northern hemisphere, the maximum pressure over oceans is overestimated by the model by 2–6 hPa. Pressure errors in winter in the model INMCM4.0 are similar to the errors of the model INM-CM48, but the Aleutian minimum is shifted to the North, and the magnitude of errors over the Atlantic region and Eurasia is somewhat larger. All models underestimate the pressure over Eurasia and overestimate it over the North Atlantic and North Pacific Ocean in summer. The norms of simulation errors of the mean annual pressure for the models INMCM4.0, INM-CM48, and INM-CM5 are 2.15 hPa, 1.98 hPa, and 1.86 hPa, respectively.

The simulation results for the atmospheric dynamics at altitudes up to 10 hPa are illustrated in Fig. 2 presenting the mean annual errors of temperature and zonal wind velocity averaged along the longitude. In the troposphere in tropics, the underestimation of temperature is about 2 degrees, and at high latitudes in the lower troposphere it is by 2–4 degrees warmer than observed. A small underestimation of temperature in the tropical troposphere and overestimation at higher latitudes are typical for many climate models including INMCM4.0 and INM-CM5. The underestimation of the temperature by 6 degrees in the polar tropopause in both hemispheres is also typical for most modern climate models. The overestimation of the temperature near the tropical tropopause has decreased in comparison with the INMCM4.0 version due to inclusion of the penetration of upward air flow into the parameterization of the deep convection slightly higher than the level of zero buoyancy. In most parts of the stratosphere the temperature is underestimated by 2–6 degrees. The cause is a not enough accurate adjustment of the ozone mass above the first calculated level. In the INM-CM5 model that uses the same parameterizations, but a higher upper boundary, the underestimation of the temperature in the stratosphere is present, but it does not exceed 2 degrees at altitudes of 10−50 hPa . The wind velocity demonstrates a negative error (more easterly wind) in the tropical troposphere and a more western wind in moderate Northern latitudes. The model INM-CM5 has a similar error too, but it has a smaller value. The stratosphere is dominated by a stronger Western stream, most of all its speed is overestimated in the region of maximal velocity of the West wind. In the INM-CM5 model such error is smaller.

Figure 3 shows the reproduction quality for temperature and salinity fields of the ocean at different depths. At depths greater than 500 m and at almost all latitudes the temperature is underestimated in the model by 0.5−1.5 degrees. Many climate models overestimate the temperature at depths about 1000 m., the overestimation of the model INMCM4.0 reaches 3–4 degrees. The reduction of the systematic error and even the change of its sign occurred as the result of introduction of the background vertical diffusion coefficient variable in depth, which increases at depths exceeding 1000 m. The salinity is underestimated in the upper 500-meter layer, and deeper than 500 meters it is overestimated. Such error in salinity is typical for many climate models. On the contrary, in the Arctic the salinity is overestimated especially at the surface. A probable cause relates to disregarding the penetration of saline plumes into the depth during formation of ice. Temperature and salinity errors in the INM-CM5 model are similar to those in the INM-CM48 model, but have smaller values.

The INM-CM48 model, like the INM-CM5 model, slightly overestimates the area of sea ice in the Arctic in all seasons. For example, in September the area is about 6 million km^2 according to observations [5], but according to the model it is about 7 million km^2. The overestimation by 1–1.5 million km^2 persists in all seasons. In Antarctic, the INM-CM48 and INM-CM5 models underestimate the sea ice area 1.5–2 times, and in February

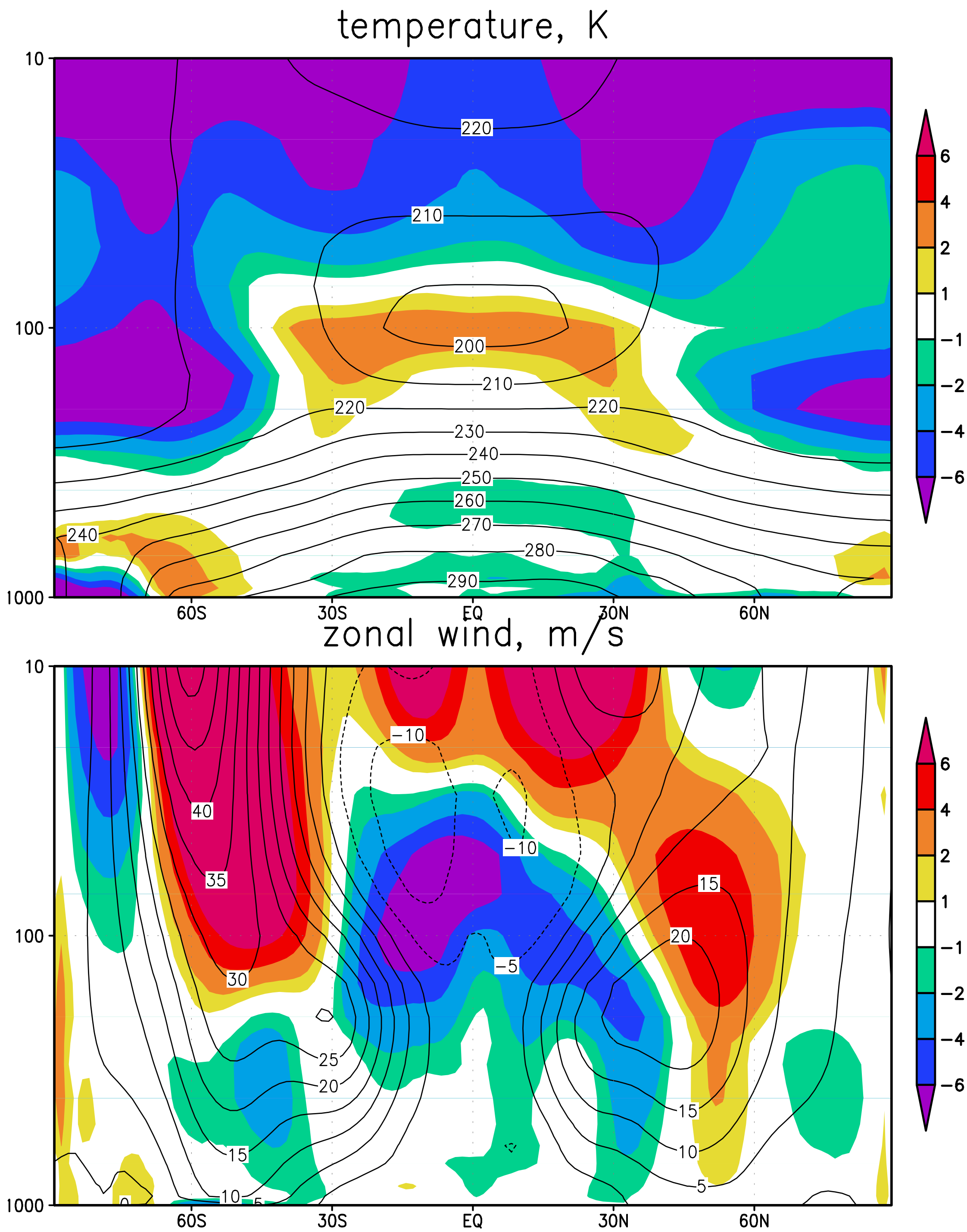

Fig. 2: Difference of mean annual temperature, K (above) and zonal wind velocity, m/s (below) according to the INM-CM48 model data and ERA Interim reanalysis. The color indicates the difference, isolines correspond to model data.

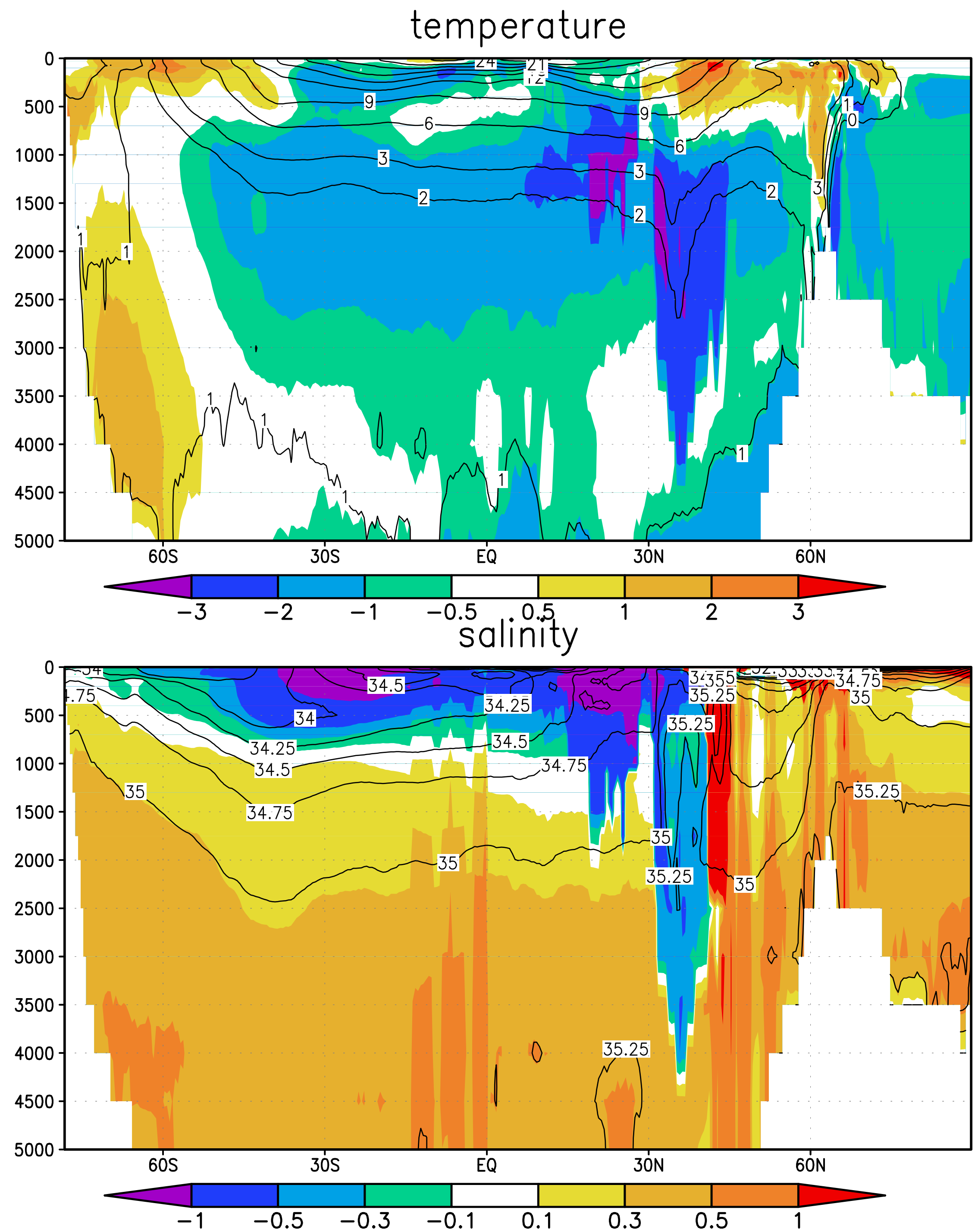

Fig. 3: Difference of mean annual temperature, K (above) and salinity, ppm (below) according to the INM-CM48 model data and [2]. The color indicates the difference, isolines correspond to model data.

and March more than twice. This error is typical for all versions of INM climate models and in general for many modern climate models. The cause of this is not clear at the moment and needs further research.

The El Niño phenomenon is reproduced by the INM-CM48 model, as well as by the INM-CM5 model, and the maximum of ocean surface temperature (OST) variability occurs in the Eastern part of the Equatorial Pacific Ocean and areas near the coast of southern America, as well as in observations. However, the amplitude of the phenomenon is underestimated 1.2–1.5 times. The observed spectral peak of OST variability in the El Niño region near the 48-month period is well reproduced by the model. According to the observations of [6], the maximal variability of OST in the El Niño region falls on December–January and on February in the model.

The maximum of the meridional stream function in the Atlantic reaches 20 Sv, it is located at the depth of 800–1000 m and the latitude of 25–30° N. In the INM-CM5 model for the global ocean, the meridional stream function is close to that obtained in the INM-CM48 model. In the Atlantic, the maximum of the stream function is 18 Sv in the INM-CM5 model and it is located at the depth of 600–1000 m and the latitude of about 25° S.

An important indicator of the model is the reproduction of changes in the global surface temperature in historical experiment. The main features of the observed temperature process (warming in 1930–40s, stabilization of the temperature in 1960–70s, acceleration of warming in 1980–90s) are obtained in the INM-CM48 model close to observed values [8] and data obtained in similar experiments with the INM-CM5 model. Slowing of warming in early 21st century, which is clearly visible in the observational data and well obtained in the INM-CM5 model, is also obtained in the INM-CM48 model, but is not so pronounced. The cause of this effect requires further studies.

3 Conclusion

The analysis of the current climate simulation by the INM-CM48 model shows that for most of considered indicators the climate is reproduced better than with the previous version of the INMCM4.0 model, and is just a little worse than in the INM-CM5 version using the same solution methods and physical parameterizations as in INM-CM48, but having an improved spatial resolution in the ocean block and an improved vertical resolution in the stratosphere and raised upper boundary of the computation domain up to about 30 to 60 km. The improvements over INMCM4.0 are associated with the use of more advanced parameterizations of clouds and condensation and interaction of aerosols with the radiation, and also with more accurate adjustment of other parameterizations. Differences from the INM-CM5 version are caused by a coarser resolution in the ocean and the impossibility of detailed reproduction of processes in the stratosphere. In general, this INM-CM48 model is ready for numerical experiments to simulate the climate.

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