Mathematical modeling of potential catastrophic climate changes

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[1] The reproducing of modern climate and climate changes in 20 century by INM general circulation atmosphere and ocean model, and forecast of climate changes in 21 century using three scenarios with this model are shown. The model is capable to reproduce main features of observed climate and climate changes in 20 century. At the end of 21 century according to INM model global warming for scenarios A2, A1B, B1 equals 3.5, 2.6 and 2.0 degrees, it is not far from the average over 20 models that took part in the model comparison. The strongest warming is produced in Arctic and at the continents in midlatitudes. During global warming, the strongest decrease of sea ice is expected in Arctic at the end of summer, where sea ice can melt completely or almost completely at the end of 21 century. In winter decreasing of Arctic sea ice area can be as large as 20–30% of modern value. Sea level rise due to thermal expansion can be equal 13–20 cm in 2100 and 25–45 cm in 2200. During global warming, increasing of precipitation, increasing of river runoff and soil moisture in high and midlatitudes is expected by 10–30%. Decreasing of precipitation is expected in many subtropical regions, especially in Mediterranean and Central America. In Russia expected warming is stronger than the global averaged one. For scenario A1B, global warming is 3.3 degrees, winter warming in Russia is 4–6 degrees in the south, and 8–10 degrees in the north. In the coldest winter months warming can be stronger than that one in all winter months. In the warmest winter months warming can be smaller than that one in all winter months. Predicted summer warming in Russia equals 5–6 degrees in the south, and 3–4 degrees in the north. In the warmest summer months warming can be stronger than that one in all winter months. In the coldest summer months warming can be smaller than that one in all winter months. Over the most part of Russia increasing of precipitation by 1.1–1.5 times is expected. The exception is southern Russia, where decreasing of precipitation by 10–20% is predicted. At the end of 21 century increase of vegetation period by 20–50 days and decrease of number of frost days by 20–50 is predicted.

INDEX TERMS: 1605 Global Change: Abrupt/rapid climate change; 1626 Global Change: Global climate models; 3367 Atmospheric Processes: Theoretical modeling; 3394 Atmospheric Processes: Instruments and techniques; *KEYWORDS:* catastrophic climate changes, mathematical modeling, INM general circulation atmosphere and ocean model.

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Introduction

[2] Prediction of future climate changes is a key problem in the modern climate science. To solve this problem, one needs to take into consideration all the factors affecting the climate and its changes. Currently, the most popular line of climate change research is to perform numerical experiments based on models of general circulation of atmosphere and ocean, which treat all key processes of climate impact with the most reasonable way at the moment. Climate changes can be conditionally divided into two types. The first type includes the changes caused by influences that are external to the climate system; for example, variations in the concentrations of greenhouse gases, aerosols, solar constant, etc. The second type of changes is conditioned by the oscillations in the climate system unrelated to external influences. The

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numerical experiments with models [*Houghton et al.,* 2001; *Volodin and Diansky,* 2006] indicate that the forced climate changes in the next couple of centuries will most likely be more significant than the natural oscillations. It is these forced climate changes caused by variations in the concentrations of greenhouse and other gases that are considered in this paper.

Numerical Experiments

[3] The simulation of climate and its changes is based on the INM atmosphere-ocean general circulation model [*Diansky and Volodin,* 2002; *Volodin and Diansky,* 2003; *Volodin and Diansky,* 2006]. The model resolution is 5 x 4 degrees by longitude and latitude, respectively, with 21 vertical levels from the Earth's surface up to a height of 30 km for the atmosphere, and 2.5 x 2 degrees by longitude and latitude, respectively, with 33 levels by depth for the ocean. The model describes all principal processes of a climate impact. Using the model, numerical experiments were performed with given timing for all main influences of climate impact in the XX–XXII centuries: the concentration of greenhouse gases (carbon dioxide, methane, and nitrous oxide) as well as volcanic and sulfate aerosols, and the solar constant. The external influences are given by observation data for the time period before 2000 and by scenarios A2, A1B, and B1 for the time period after 2000.

[4] The numerical experiments include:

[5] (1) Simulation of climate changes between 1871 and 2000 based on the observed change in all external influences.

[6] (2) Simulation of climate changes in the XX–XXII centuries for scenarios A2, A1B, and B1 of the variation in the concentrations of greenhouse and other gases in the XXI century. The solar constant and concentration of volcanic aerosols in these experiments were fixed at the level of the year 2000. For the XXII century, all external influences were assumed to be fixed at the level of the year 2100.

[7] (3) Simulation of the XXI century climate, where all gas concentrations and the remaining influences were assumed to be equal to the values observed in 2000 (experiment 2000).

[8] (4) Control experiment, where all external influences correspond to 1871 data. This experiment is needed to estimate the inner variability of the climate system.

[9] The concentration of carbon dioxide (which is the key greenhouse gas) was 289 ppm in 1871, 370 ppm in 2000, and can reach 550, 690, and 830 ppm for scenarios B1, A1B, and A2, respectively, in 2100. The XX century was characterized by increased concentrations of the remaining greenhouse gases and sulfate aerosol. The solar constant also has a tendency of growth; however, its contribution to the temperature increase in the XX century constitutes merely 10 to 15% of the contribution of greenhouse gases. The maxima of volcanic aerosol concentrations correspond to powerful volcanic eruptions with dust particles falling into the upper layers of the atmosphere and being able to remain there from a few months to a few years.

Results

[10] It is known that XX century was characterized by increased values (by 0.6–0.7°C) of the globally averaged near-surface air temperature. To be able to adequately predict the future climate changes, the model is required to adequately reproduce the climate changes occurred in the XX century. Figure 1 shows the temporal evolution of the surface temperature based on observation data [*Jones et al.,* 1999], on data of five numerical experiments using the INM RAS model with XX-century observed changes in the concentrations of greenhouse gases and other external influences, as well as on data of 3 numerical experiments where all influences were fixed at the level of 1871. In addition to the mentioned general warming in the XX century, there were also an observed warming in the 1940–50s and some cooling in the 1960–70s. In all numerical experiments with actually observed influences in the XX century, the temperature increases by 0.7–0.9°C, which is close to or slightly higher than the observed warming value. In addition, these experiments yield a slight maximum of temperature in the 1940–50s and a slowdown in the warming in the 1960–70s. An analysis of the numerical calculations shows that the XX-century warming is mostly due to increased concentrations of greenhouse gases, which is partially compensated by the cooling caused by increased concentrations of sulfate aerosols. The slight maximum of temperature in the 1940–50s is caused by the enhanced level of solar radiation and by the absence of volcanic aerosols in these years, while the slowdown in the warming in the 1960–70s is connected [*Meehl et al.,* 2004] with the decreased value of solar radiation and frequent volcanic eruptions.

[11] The three experiments with constant-in-time influences fixed at the 1871 level show that there is no warming in the XX century (Figure 1). This means that the warming observed in the XX century appears to be the caused by not only the inner variability of the climate system. An analysis of the results of other models also shows that none of these models succeeded in obtaining the value of warming by 0.6–0.7°C during the century for fixed concentrations of greenhouse and other gases [*Brocoli et al.,* 2003; *Meehl et al.,* 2004].

[12] Figure 2 presents a prediction of variation in the globally averaged temperature in the XXI century derived by the INM RAS model. The temperature increase in the late XXI century as compared to 1981–2000 will constitute around 3.5°C for scenario A2. The value averaged over all models involved in this experiment is equal to 3.4°C, and the scattering between all models is in the range between 2.3°C and 3.9°C. The warming value in the INM RAS model for scenario A1B is some 2.6°C, and the model-averaged value is 2.7°C, with a scattering between all models from 1.9°C to more than 4°C. The warming value in the INM RAS model for scenario B1 is some 2°C, while the model-averaged value is 1.8°C, with a scattering between all models in the range between 1.0°C and 3.3°C. Thus, for all the scenarios, the warming value predicted by the INM RAS model is close to that averaged over all models. Even if the concentrations of all gases are kept unchanged at the level of 2000, the model predicts a temperature increase during the XXI century by

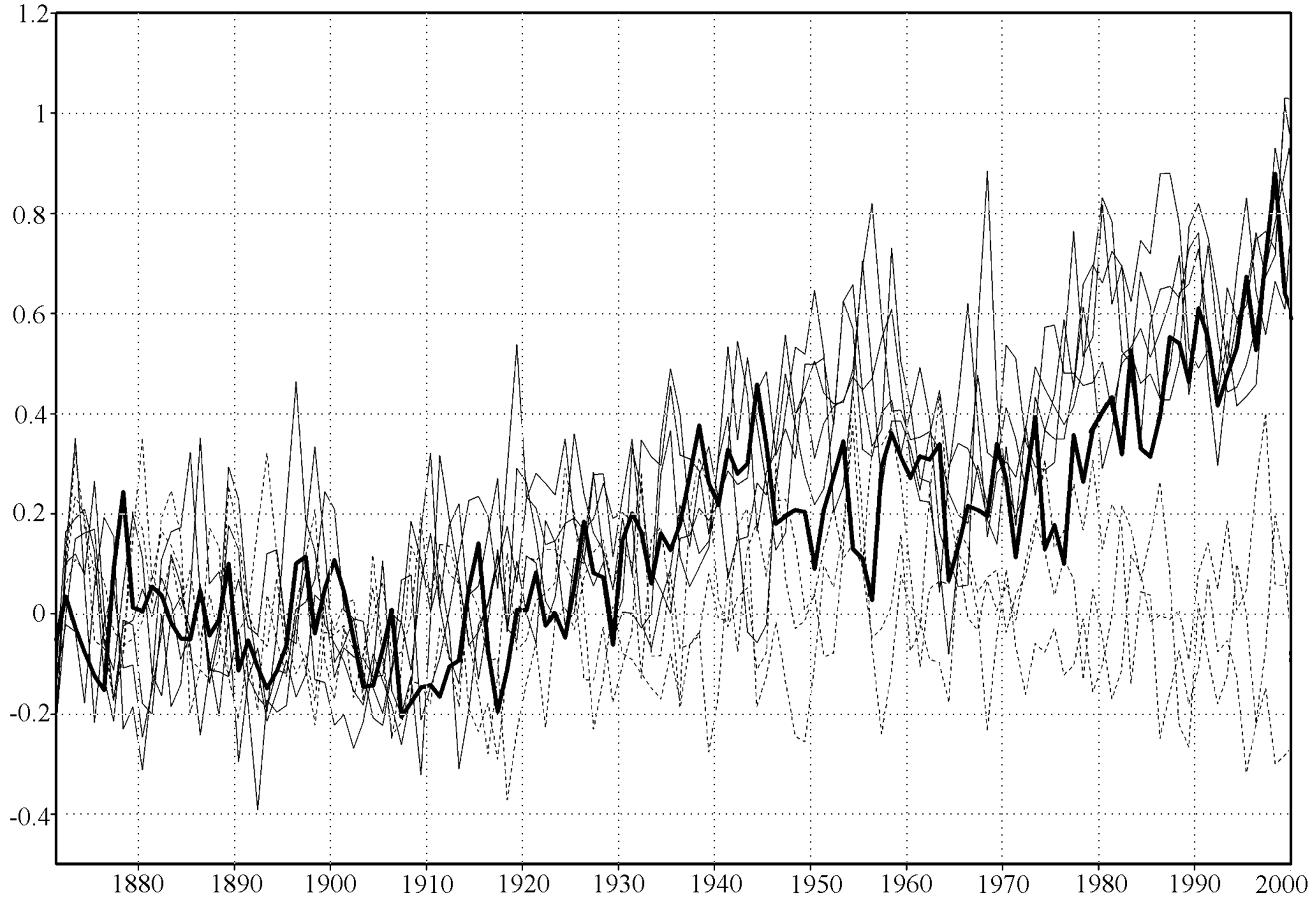

Figure 1. Changes in the globally averaged air temperature (degrees) in 1871–2000 by observation data (bold solid line), by the results of 5 numerical experiments with observed changes of external influences (thin solid lines), and by the results of 3 numerical experiments with external influences fixed at the level of 1871 (dashed line). The value averaged over the period from 1871 to 1920 was excluded.

almost a degree, which is connected with thermal inertia of the ocean.

[13] The temperature increase in global warming is not the same for different geographical areas and seasons of the year. According to the results of the INM RAS model, the warming in December–February will be the strongest in the Arctic (constituting more than 10°C), where the ice in many regions will turn from multiyear to seasonal. The warming is significantly higher than the average value at moderate latitudes of Eurasia and North America, where the temperature increase reaches up to 5–7°C. The expected value of warming is some 3°C in the continental tropics and 1–3°C over most of the oceans. The lowest temperature increase is expected in the southern ocean. In June-August, the maximum warming (reaching up to 10°C) is concentrated in the vicinities of Antarctica. In summer, at moderate latitudes of Eurasia and North America, the expected value of warming is 2–4°C, which is smaller than the value of winter warming. Unlike winter, the summer temperature increase in the tropics is stronger than at moderate and high latitudes. These geographic features of global warming are inherent to the predictions calculated with the help of most models [*Houghton et al.,* 2001].

[14] The amount of precipitation at moderate and high latitudes will increase by 10–20% of the current value. The amount of precipitation in most of the subtropics will decrease, with the most considerable decrease being registered in the Mediterranean as well as in Central America and the Atlantic areas adjacent to it. In many near-equatorial areas, the amount of precipitation will slightly increase by global warming. These features of the redistribution of precipitation are also typical to the majority of modern models. In line with this, there will be a 10–20% increase in the river runoff and moisture content in soil at the most part of moderate and high latitudes and a decrease of the same value in the most part of subtropical areas. The most considerable

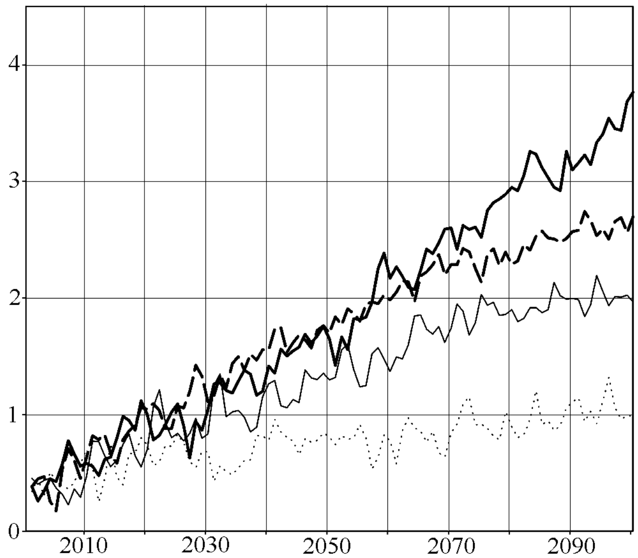

Figure 2. Changes in the globally averaged air temperature in the XXI century as compared to the period from 1981 to 2000 by the INM model for scenarios A2 (bold solid line), A1B (bold dashed line), B1 (thin solid line), and 2000 (thin dashed line).

decrease in the soil humidity will be registered in the Southern Europe, Near East, and Middle East. In near-equatorial areas, one may expect an increase in the soil moisture.

[15] In the late winter, the model-calculated area of sea-ice cover in the Northern hemisphere in the XX century constitutes 12–13 million km2, which is close to the estimates from observational data. In the late XX century, the decrease in the area of sea-ice cover starts to exceed the value of the natural interannual variability. In the XXI century, the area of sea-ice cover decreases further. The data for the three scenarios under consideration differ from one another only slightly. The model-calculated area of sea-ice cover in the late XXI century will be 10, 9.5, and 9 million km2 for scenarios A2, A1B, and A2, respectively. In other words, the area of sea-ice cover in the late XXI century will decrease by 20–30% according to the numerical prediction. In the late summer, the change in the area of sea-ice cover is much more substantial. In the early XXI century, the model-calculated area of sea-ice cover in the Northern hemisphere will decrease by 25% as compared to the first half of the XX century, which is consistent with the existing estimates from observational data [*Waple et al.,* 2004]. In the late XXI century, the area of sea-ice cover in September can constitute almost 20% of the area obtained for the XX century under scenario B1, almost 10% for scenario A1B, and almost completely vanishing for scenario A2. The majority of other models also yield significant changes in the area of sea-ice cover in the Northern hemisphere in the late summer, and in the late XXI century the Arctic ice melts downs completely or almost completely.

[16] A key aspect of global warming is the sea-level rise. According to *Houghton et al.* [2001], the sea-level rise in the XX century constituted 10–15 cm, caused mainly by thermal expansion of ocean waters. The next important factor influencing on the sea-level change is the melting of mountain glaciers, which contributes to only 30–40% of the total sea-level rise in the XX century, according to the estimates of *Bindoff and Billebrand* [2007]. These estimates suggest that the melting of continental ices in Greenland and Antarctica has practically no contribution to the observed sea-level rise. Normally, mountain glaciers are of small area and taken to be subgrid-scale in climate models; therefore, the contribution of their melting to the rise of ocean level now is unlikely to be represented in climate models. However, the thermal expansion is a large-scale effect and can be adequately reproduced by models.

[17] According to the results obtained by the INM RAS model, in the XX century the sea-level rise due to the thermal expansion was some 5 cm. All models involved in the intercomparison yield a value of the sea-level rise between 0 and 8 cm. The observation-based estimate of the contribution of the thermal expansion to the sea-level rise is 6–10 cm. Thus, the majority of models, including the INM RAS model, slightly underestimate the observed rise of ocean level due to thermal expansion.

[18] The value of the rise of the world-ocean level due to thermal expansion obtained by the INM RAS model for 2010 as compared to 2000 is 20 cm for scenario A2 (see Figure 3), while all other models yield a value in the range between 14 and 34 cm. For scenario A1B, the INM RAS yields a value of 17 cm, while all other models yield a value in the range between 12 and 35 cm. For scenario B1, the INM RAS yields a value of 13 cm, while all other models yield a value in the range between 9 and 27 cm. Thus, the estimates for the world-ocean level change by the INM RAS model are in the

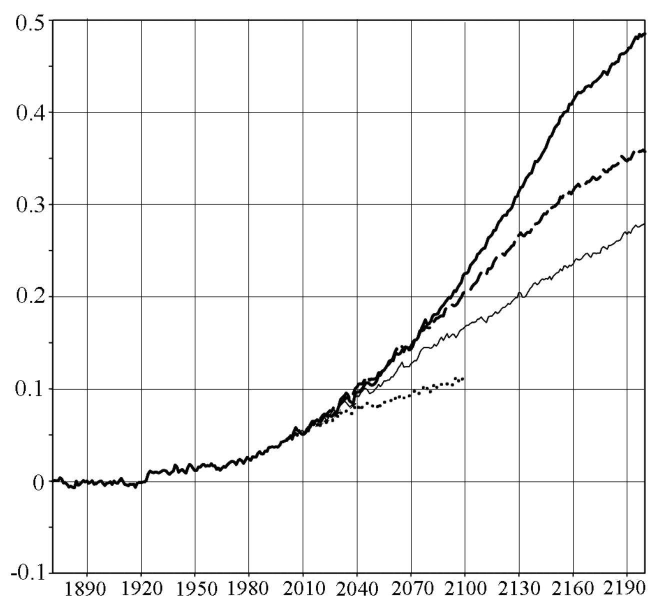

Figure 3. Sea-level change (m) due to thermal expansion in the experiment for the XX century and for the experiment 2000 (thin dashed line), for scenarios B1 (thin solid line), A1B (bold dotted line), and A2 (bold solid line).

lower half of the scattering of this value over all models. In view of the fact that the near-surface warming in the model is close to the averaged value, it can be inferred that the INM RAS model warms up a slightly smaller layer of the ocean than the layer averaged over all models. For fixed concentrations of greenhouse gases in the XXII century, due to thermal inertia of the ocean, the ocean-level rise will be continued, reaching values of 48, 36, and 28 cm for 2200 calculated by the INM RAS model for scenarios A2, A1B, and B1, respectively, as compared to the early XX century. The results of numerical calculations carried out by the INM RAS model indicate that in the XXI and XXII centuries, the contribution of melting of the Greenland and Antarctic ices to the rise of the ocean-level rise remains small in comparison with the thermal expansion.

[19] Now, we analyze the climate changes in the territory of Russia. Let us consider not only the variation of values averaged over a long time period, but also extreme weather conditions. The warming value averaged over all the Earth is around 3.3°C for scenario A1B. On the territory of Russia, the winter warming exceeds the average value and constitutes from 4°C in the south to 6–8°C in central regions and 8–9°C in the north. The warming over the Arctic exceeds 10°C. In the warmest winter months, the warming is smaller than the average value and constitutes mainly 3–6°C except for some regions of central Siberia, where the warming value reaches up to 6–8°C. On the contrary, in the coldest winter months, the warming is higher than the average value and constitutes in the most part of Russia 8–12°C (Figure 4).

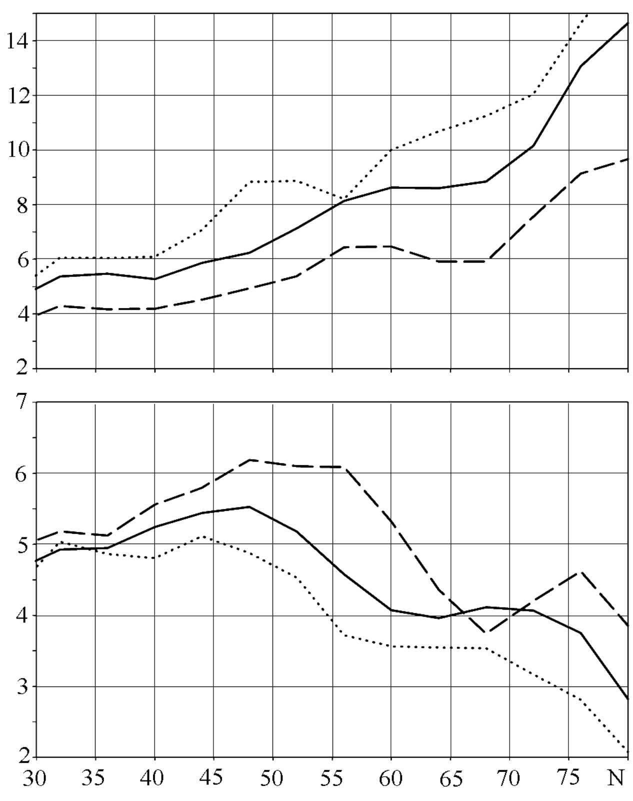

Figure 4. Change in the temperature (degrees) in December–February (top) and June–August (bottom) by the results of the INM model for all months (solid line), for the warmest months (dashed line), and for the coldest months (dotted line) in 2101–2200 for scenario A1B in comparison with 1901–2000. Data are averaged from 30° to 130° E.

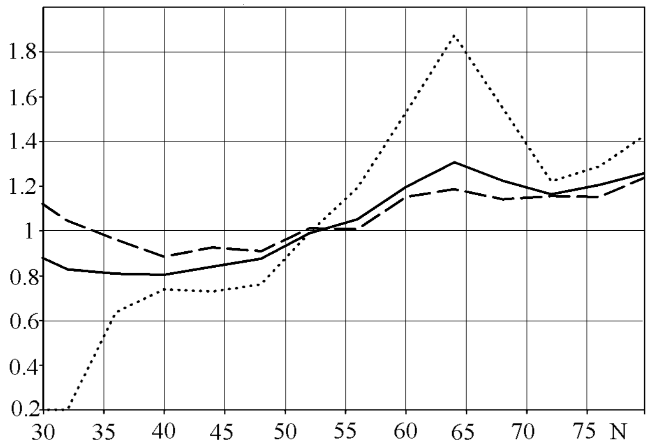

Figure 5. Relative variation of precipitation from 2101 to 2200 for scenario A1B in comparison with 1901 to 2000 for summer (May to September). For all months (solid line), for the months with highest humidity (dashed line), and for the driest months (dotted line).

[20] In summer, the warming in Russia is a maximum in the south, reaching there up to 5–6 °C, and a minimum on the Arctic coast, with a value of 3–4°C. In the warmest summer months, the temperature rise caused by global warming is somewhat stronger than on the average over all summer months, with a warming value in the south reaching 6–7°C. In the coldest summer months, the temperature rise is weaker than on the average. Thus, in global warming, the climate extremity with respect to temperature declines in winter and rises in summer. This occurs due to the fact that the extreme temperature situations emerge through different mechanisms.

[21] Figure 5 shows the variation of precipitation on the territory of Russia from 2101 to 2200 for scenario A1B in comparison with 1901 to 2000 for summer (May to September). In the northern half of this territory, there occurs a precipitation rise by a factor of 1.1–1.5. The decline in precipitation down to 0.7–0.9 of the average value in the course of the XX century is registered in south Russia and clearly expressed in southern Europe (around the Mediterranean). The relative variations in precipitation in the months with highest humidity for the Russian territory north of 55?N constitute a value between 1.1 and 1.3. In the south, where the amount of precipitation decreases on the average, this amount in the extreme rainy months in global warming shows no considerable changes. On the contrary, in the months of highest dryness, the amount of precipitation in the Russian south as well as in the most part of Central Asia and the Mediterranean decreases by a factor of 1.5–4. Thus, in dry regions the months of highest dryness are characterized by specifically enhanced dryness. In northern

regions, the global warming makes the amount of precipitation in the months of highest dryness to increase by a factor of 1.3–1.7; i.e., droughts become less expressed.

[22] Under global warming on the territory of Russia, there will occur also a noticeable growth in the vegetation period. The growth is expected to be the highest (up to 40–50 days per year) in 2001–2100 for scenario A1B in comparison with 1981–2000 in central regions of the European part of Russia. This is closely connected with the reduced number of frosty days per year. In Siberia as well as in the south of Russia, the growth in the vegetation period and the reduction of frosty days constitutes 20–30 days per year.

[23] Let us consider also the extent of permafrost in soil. In 2081–2100 the permafrost boundary will move northeastward from the current position by almost 1000–1200 km for scenario B1 and 1000–1200 km in addition for scenario A2. In the latter case, the continuous permafrost areas will be present only in Taimyr and the Arctic coast of East Siberia, while sporadic permafrost areas will be found only in the Siberian polar region.

Conclusions

[24] Based on the INM RAS atmosphere-ocean general circulation model, we have analyzed some results of the reproduction of the observed climate and its changes in he XX century and estimated the climate changes expected for the late XXI century, for three scenarios of the concentrations of greenhouse and other gases. The observed global warming by 0.6–0.7°C in the XX century is most likely caused by enhanced concentrations of greenhouse gases, since a similar warming is obtained in all 5 calculations with observed changes in the concentrations of all gases, but in none of the three calculations where the concentrations of all gases are fixed at the level of 1871.

[25] The results of the INM RAS model indicate that in the late XXI century the value of global warming will be 3.5°C, 2.6°C, and 2.0°C for scenarios A2, A1B, and B1, respectively, which is close to the estimates of global warming averaged over all 20 models involved in the intercomparison project. The strongest warming is expected to be in the Arctic and continents at moderate latitudes. The global warming will lead to a reduction in the area of sea ice, with the most considerable reduction taking place in the late summer in Arctic, when the predicted ice cover in the late XXI century will melt down completely or almost completely. In winter, the reduction of the area of sea-ice cover may be some 20–30% of the current value. According to the INM RAS model results, the rise in the level of the world ocean due to thermal expansion may constitute 13–20 cm by 2100 and 25–45 cm by 2200. Under global warming, it is expected also that the amount of precipitation will grow by 10–30% at moderate and high latitudes and, caused by this, the soil humidity and river runoff will increase. The amount of precipitation may decrease in many subtropical areas, especially, in the Mediterranean and Central America.

[26] The warming on the territory of Russia is expected to be higher than the value averaged over the Earth. For scenario A1B under the global warming value of almost 3.3°C, the winter warming in Russia will be from 4–6°C in the south to 8–10°C in the north. In the coldest months of winter, the warming is expected to be stronger than, and in the warmest months to be weaker than on the average in winter. In summer, the warming in Russia will constitute from 5–6°C in the south to 3–4°C in the north; in this case, in the warmest (coldest) months of summer, the warming is expected to be stronger (weaker) than on the average in summer. On the most part of Russia, the amount of precipitation is expected to grow by a factor of between 1.1 and 1.5, except for the south, where a decrease by 10–20% is expected. An increase in the amount of precipitation in the months of highest humidity is expected in almost all the territory of Russia by a factor between 1.1 and 1.3, except for the south, where this value will not be significantly changed. In the driest months, a reduction in the amount of precipitation is expected for the south by a factor of 1.5–2, and a precipitation increase of the same factor is expected in the most part of the remaining territory. In the south, one expects an extension of the maximum duration of the no-precipitation period by 2–6 days, while in the northern part of Russia, a reduction by 1–3 days is expected. In the most part of the territory of Russia, one also expects a growth in the number of days with precipitation of more than 10 mm by 2–6 days, except for the south, where the number of these days will not be significantly changed.

[27] By the late XXI century in Russia, there will be a noticeable (by 20–50 days) growth in the length of vegetation period and a reduction of frosty days. The growth is expected to be the highest in central regions of the European part of Russia. By the late XXI century, one predicts a considerable reduction in the area of permafrost.

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