Possible regional consequences of global climate changes

I. I. Mokhov[1]

Received 12 July 2008; accepted 4 August 2008; published 30 September 2008.

[1] The present article deals with possible global and regional changes of climate in the 21st century with different scenarios of natural and anthropogenic impacts given in comparison to the estimates of contemporary changes according to observations data. The results of analysis of numerical simulations with global climatic models and of the more detailed regional simulations are described. Possible changes are analyzed, taking into account the carbon cycle in climatic models, including the methane cycle. Together with temperature the changes of precipitation, river runoff, bioproductivity of terrestrial ecosystems are estimated. Moreover, the article describes the characteristics of extreme regimes, including extreme precipitation, droughts and fires. The relative contribution of natural (solar and volcanic activity) and anthropogenic factors, for the entire globe and for the regions with considerable temperature changes over the last decades are also evaluated. *INDEX TERMS:* 1605 Global Change: Abrupt/rapid climate change; 1616 Global Change: Climate variability; 1631 Global Change: Land/atmosphere interactions; 1637 Global Change: Regional climate change; *KEYWORDS:* climate changes, global climatic models, natural and anthropogenic impacts, parameters of extreme regimes.

Citation: Mokhov, I. I. (2008), Possible regional consequences of global climate changes, *Russ. J. Earth. Sci., 10,* ES6005, doi:10.2205/2007ES000228.

[2] Over the past century the global surface temperature has increased by 3/4°C. It indicates the acceleration of global warming. Over the last century and a half the temperature has increased at a speed of less than 0.05 K a decade, over the past half-century – 0.13 K over a decade and over the last quarter of a century – at a speed of 0.18 K a decade [*Solomon et al.,* 2007]. Now the global temperature is growing at 0.2 K over a decade or 2 K a century – the threefold growth than in the 20th century.

[3] According to the data of CRU (http://www.cru.uea.ac.uk/), based on the instrumental observations carried out from the middle of the 19th century, from the last 11 years (1997–2007) 10 were years with the highest global sueface air temperature. The warmest globally were 1998 and 2005. The warmest for the Northern Hemisphere were 2005, 1998 and 2007. 2007 was the eighth globally abnormal year and the third in the Northern Hemisphere. January 2007 was the warmest January in the Northern Hemisphere and the whole Earth over the total period of instrumental observations from the middle of the 19th century. The winter season starting in December 2006 to February 2007 was also the warmest winter in the Northern Hemisphere, for the Earth as a whole. We can add that in the Northern Hemisphere the last 5 Septembers (2003–2007) were the warmest with a record abnormal September in 2005. It is worth mentioning that in September 2005 the minimal extent of Arctic sea ice was observed according to satellite data starting from the end of the seventies. In September 2007 this record was also broken (http://nsidc.org/).

[4] Various data based on instrumental observations (including satellite data) correlate with each other as a whole. However some differences are revealed, related to global evaluations of anomalies of different years. Thus according to GISS data (http://data.giss.nasa.gov/) the warmest temperature at the Earth's surface during the period of instrumental observations from the end of the 19th century was recorded in 2005, 1998, 2007 and 2002. January 2007 from meteorological observations for the whole globe was by 1.1 K warmer than over the basic period 1851–1980 and by 0.2 K warmer than January 2005 – the second abnormal month. Globally record months in 2007 according to GISS data based on meteorological observations were also August and April.

[5] In Russia, as a northern country, the warming is growing faster, than for the Earth as a whole (see, for example, [*Gruza and Rankova,* 2003, 2006; *Mokhov,* 2006a; *Mokhov et al.,* 2006a]). In some regions of Russia, in particular in Siberia, the acceleration rate of annual-mean temperature is more than 4 times higher than that of the global temperature (to and more than 0.8 K over a decade). It's noteworthy that last year 2007 was the warmest in Russia according to the data of Rosgidromet from 1891. Moreover it was the

[1] A. M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow, Russia

ISSN: 1681–1208 (online)

warmest year overland of the Northern Hemisphere according to the data of CRU from the middle of the 19th century.

[6] The extreme rates of regional warming are observed in winter in Siberia [*Gruza and Rankova,* 2006; *Mokhov,* 2006a; *Mokhov et al.,* 2006a]. Over the larger part of the territory of Russia in winter significant positive trends of temperature are recorded, but in some northern regions the trends are significantly negative. Nevertheless the trend of annual-mean temperature in these regions was positive. The maximal positive trends of temperature in high latitudes and in the north-east of Eurasia (in Chukotka) in spring were recorded. It is related to the fact that the albedo-temperature feedback, depending on snow-ice cover thaw caused by the warming, manifests more efficiently in higher latitudes (with low winter temperature and stable snow cover) later – in spring. In summer temperature trends almost everywhere in Russia are positive, but weaker, than in winter.

[7] Warming in general changes dates and duration of the vegetation period with subsurface temperature over 5°C. Over a large part of the territory of Russia the increase of the vegetation period was noted. It is related to both the earlier beginning of spring and later autumn. At the same time the opposite tendencies are revealed in a number of regions.

[8] The increase of surface air temperature, detected in Siberia and also in Alaska over the last decades, was the highest in the Northern Hemisphere. In the Southern Hemisphere significant warming was noted on the Antarctic Peninsula (see [*Mokhov et al.,* 2006a]).

[9] It has to be noted that the general trend of warming not only doesn't exclude extremely negative temperature anomalies occurring at a regional level (as, for example, in the winter of 2006 in Russia), but can even facilitate their increase. It is indicated by the results of modeling simulations in comparison with the observations for atmospheric blockings, connected with extreme frosts in winter and droughts in summer [*Mokhov,* 2006b].

[10] The most advanced modern climate models can reproduce the basic global and regional climatic changes, noted over the past decades (see, for example, [*Houghton et al.,* 2001; *Solomon et al.,* 2007]). The results of model study have shown the significant difference between the warming of the thirties and beginning of forties of the 20th century and the warming of the last decades. The first one could be explained by natural reasons, related, in particular, to changes of solar irradiation and volcanic activity. The last warming according to simulations is essentially caused by the anthropogenic factor – the increase of greenhouse gases in the atmosphere, mainly carbon dioxide [*Houghton et al.,* 2001; *Solomon et al.,* 2007]). According to the simulations with the IAP RAS climate model only not more than one-fourth of the global warming, recorded over the past decades, can be explained by variations of solar irradiation [*Mokhov et al.,* 2006b].

[11] In [*Mokhov and Smirnov,* 2008] the analysis of comparative impact of various natural factors (solar and volcanic activity) and anthropogenic influence (changes of carbon dioxide content in the atmosphere) on the global surface air temperature according to the data over the last century and a half (1856–2006) with the evaluation of parameters of Granger causality was carried out. The statistically important impact of all three factors on the global temperature was revealed. The most significant was the anthropogenic factor. The impact of solar and volcanic activity was estimated as considerably weaker. According to the evaluations obtained the increase of global surface air temperature over the past decades can be explained only by taking into account the changes of CO_2 content in the atmosphere.

[12] In [*Mokhov et al.,* 2006a] an ability of the climate model of general circulation (CGCM) to reproduce temperature changes in the regions with considerable warming trends at the surface over the last decades was analyzed – in Siberia and Alaska in the Northern Hemisphere and on the Antarctic Peninsula in the Southern Hemisphere. The role of natural and anthropogenic factors was evaluated. A conclusion was made that the best climate models of global circulation can adequately reproduce temperature changes in the regions with extreme trends of warming over the last decades. In particular, a relatively good correlation of positive trends of annual-mean surface air temperature in Alaska and the Antarctic Peninsula was obtained. According to the model results in the regions with highest rate of surface air warming at the end of the 20th century the primary part in these changes was related with anthropogenic influence. It has to be noted that the results of model simulations with different initial conditions have shown that under the global anthropogenic warming negative regional temperature trends can reveal in separate numerical runs even for the regions with the highest rate of the regional warming of climate at the end of the 20th century.

[13] The modern rate of global warming correlates with earlier model simulationns made at anthropogenic scenarios of increasing emissions of carbon dioxide, methane and other greenhouse gases and aerosols to the atmosphere. Over the last years the changes of some climate characteristics occurred even faster than it was predicted by model estimations of anthropogenic scenarios, that just recently seemed excessively catastrophic. This is related, for example, to the sea ice extent in the Arctic.

[14] Arctic sea ice extent in September (with minimal arctic sea ice area in the annual cycle) according to satellite data from 1979 to 2007 (http://nsidc.org/) occurs at a speed of about 10% over a decade (over 70,000 km^2 per year). In September 2007 the overall area of Arctic sea ice only slightly exceeded 4 mln km^2. In the end of the seventies and in the beginning of the eighties it was no less than 7 mln km^2. The satellite data have shown that the ice season for some areas has become shorter by two months and more.

[15] According to the simulations using the CGCM ensemble by the end of the 21st century at the moderate anthropogenic scenario the Arctic navigation can prolongate on a period from 3 to 6 months along the Northern Sea Route, and from 2 to 4 months for the Northwest Passage. It has to be mentioned that the Northwest Passage in the 21st century opens for navigation considerably later than the Northern Sea Route (V. Ch. Khon et al., 2008, submitted).

[16] Contemporary global warming over the last centuries isn't accompanied by warming at the surface in high latitudes in the Southern Hemisphere – in the Antarctic (except for the Antarctic Peninsula). The area of Antarctic sea ice

also hasn't significantly changed, in contrast to the Arctic sea ice.

[17] Among the global warming consequences some are significant for Russia: increase of subsurface temperature (especially at cold season); change of precipitation regime, snow cover, soil moisture content and river runoff; sea ice extent in the Arctic; change of permafrost, cyclones and anticyclones in the middle and polar latitudes, droughts and fires.

[18] Over the last decades noticeable regional changes of the atmospheric circulation were exhibited, including those related to cyclones and centers of action, in which considerable changes are expected to occur in the future [*Akperov et al.,* 2007; *Golitsyn et al.,* 2006; *Khon and Mokhov,* 2006; *Mokhov and Khon,* 2005]. It has to be noted that long-lived anticyclones (blockings) in winter are conductive to the formation of weather regimes with extreme frosts and droughts in summer. The second half of the 20th century was characterized, for example, by a tendency towards weakening of the Siberian anticyclone and strengthening of the Aleutian cyclone. Given the tendency towards global warming in the 21st century we can expect according to model simulations a further weakening of the Siberian anticyclone in winter and a drop of sea level pressure in the Arctic.

[19] Changes in precipitation are related with changes in temperature and atmospheric circulation. Remarkable regional changes of precipitation characteristics and the hydrological cycle as a whole were noted in the 20th century and beginning of the 21st century, particularly in Russia (see, for example, [*Gruza and Rankova,* 2003]). The data analysis has shown the growing trend of extreme precipitation in different regions of the world, in particular overland in middle and high latitudes of the Northern Hemisphere [*Houghton et al.,* 2001; *Solomon et al.,* 2007]. According to [*Kiktev et al.,* 2002], for example, the data for the Northern Hemisphere in the second half of the 20th century show that in the European territory of Russia (excluding the northern regions) a trend of increasing of the number of days with heavy rainfall (snowfall) prevails. At that regional tendencies are revealed, with growing intensity of precipitation. For the northern and southern European regions of Russia (the Caucasus and Cuban) and in central Siberia the maximal number of successive days without precipitation is decreasing. According to [*Houghton et al.,* 2001; *Solomon et al.,* 2007] at the global warming in the 21st century this trend is expected to strengthen and reveal in many regions (see also [*Arnell et al.,* 2001; *Groisman et al.,* 1999; *Kiktev et al.,* 2002; *Mokhov et al.,* 2003; *Semenov and Bengtsson,* 2002]).

[20] The results of multi-model analysis (for two dozens of CGCMs models) show the significant difference of the regional trends of winter and summer precipitation over Northern Eurasia due to anthropogenic warming in the 21st century [*Khon,* 2007; *Mokhov,* 2007a]. In particular, the general increase of precipitation in the basins of Volga, Ob, Yenisey and Lena (excluding summer precipitation in the Volga basin) is related to the growing intensity of precipitation, especially in winter. At that the principal difference of changing trends of precipitation probability in winter and in summer was revealed, with the regional growth of probability of precipitation in winter and its decrease in summer [*Khon,* 2007; *Khon et al.,* 2007; *Mokhov,* 2007a, 2007b; *Mokhov et al.,* 2003, 2005a, 2006c]. The later trend facilitates formation of meteorological droughts in summer. Multi-model estimations also point out to the general growth under the global warming of the Siberian rivers runoff, falling into the Arctic Ocean, including CGCM of the Institute of Numerical Mathematics of the Russian Academy of Science and the global climate model of intermediate complexity of the Institute of Atmospheric Physics RAS (IAP RAS CM) [*Khon,* 2007; *Mokhov,* 2007a]. According to the ensemble of models the average river runoff of the Ob grows in the 21st century at the moderate anthropogenic scenario SRES-A1B more than by 10%, and the runoff of the Lena river – more than by 20%.

[21] By model estimations [*Meleshko et al,* 2004] the annual-mean global precipitation can increase by the middle and end of the 21st century approximately by 2% and 3% accordingly, and the general growth of precipitation on the territory of Russia significantly exceeds average global changes. According to the model simulations in many water basins in high and middle latitudes precipitation grows not only in winter, but in summer as well. However in the warm season the increase of precipitation is considerably smaller and reveals mainly in the north.

[22] In the southern regions of the European part of Russia in summer by model simulations the decrease of precipitation can be expected [*Meleshko et al,* 2004; *Mokhov et al.,* 2003]. In the European part of Russia and its southern regions in winter the share of rain is increasing, and in East Siberia and Chukotka – of snow. As a result the snow mass accumulation decreases in the west and south of Russia and an additional accumulation of snow occurs in Central and East Siberia.

[23] The global warming causes the growth of overland evaporation at the warmer season. It leads to a considerable decrease of soil moisture content and facilitates formation of droughts, especially for the South of Russia.

[24] Precipitation growth entails a considerably increased runoff on the majority of Russian rivers [*Meleshko et al,* 2004] (see also [*Khon,* 2007; *Mokhov,* 2007a; *Mokhov et al.,* 2003, 2005b]), excluding the basins of southern rivers (the Don, in particular). For them the annual river runoff in the 21st century decreases as a whole. The most considerable increase of river runoff in the 21st century was obtained from model simulations for the northern rivers, flowing into the Arctic Ocean, including the rivers Lena, Yenisey, Pechora and Severnaya Dvina.

[25] Maximal (spring) river runoff depends on the rate of snow thawing and of thawing of the mass of snow, accumulated in winter. Model simulations show a decrease of runoff maximum and its earlier occurrence at the Don, Volga and Ural watersheds in the 21st century. It is related to diminishing snow mass in winter. The runoff of northern rivers, including Pechora, Severnaya Dvina and Ob, increases significantly by the middle of the 21st century due to faster snow thawing, notwithstanding some decrease of the snow mass by the start of spring. By the end of the 21st century this river runoff will decrease, related to the loss of the accumulated snow mass. In Central and East Siberia, warming increases the river runoff of Yenisei and Lena, because

with the increase of snow mass in winter the river runoff also grows with snow thawing in spring. Considerable increase of spring river runoff due to the snow thawing in the river watersheds of Yenisei and Lena by model simulations for the first half of the 21st century characterizes the increase of large spring floods probability in those watersheds [*Meleshko et al.,* 2004].

[26] Forest fires in Russia constitute a considerable ecological hazard. Forest fires are also important taking into account the carbon balance. The analysis of model simulations of the fire risk indices in summer compared to satellite data not only indicate the growth of fires risk in the 21st century, but the high level of fire risk for separate Russian regions already at the present time [*Mokhov et al.,* 2006d]. For the European territory of Russia the southern border of forests correlates well with the border of moderate risk of fires for modern climate. For its Asian territory the situation is different. The higher level of the fire risk indices manifests itself in the forest areas to the east from Baikal Lake already for the modern climate conditions.

[27] The estimates of possible changes in the permafrost are particularly important for Russia [*Meleshko et al.,* 2004]. According to [*Demchenko et al.,* 2002] the sensitivity of areas with conditions favorable for formation of permafrost to the temperature regime differs considerably for various models. However, for each concrete model, it doesn't depend on the examined scenarios of anthropogenic influence, taking into account, or not, the changes of aerosol content in the atmosphere, in particular. The comparison of model results to the data of paleoclimatic reconstructions has shown that the southern border of permafrost in the territory of Russia during the Holocene optimum was close to the conditions that can be potentially achieved by the middle of the 21st century taking into account the effect of anthropogenic aerosol emission. Without aerosol emission these conditions are closer to the state of permafrost during the Eemian interglacial period. Analysis of numerical simulations with the IAP RAS climate model at different scenarios of antropogenic forcings has shown that potential area of permafrost is more sensitive to the temperature vatiations for slower changes of greenhouse gases concentration in the atmosphere and approaches the corresponding estimate for quasi-stationary paleo changes [*Demchenko et al.,* 2006].

[28] In [*Meleshko et al.,* 2004] according to the results of numerical simulations a considerable deepening of seasonal thawing depth was obtained for the regions of Russia under the anthropogenic climate warming by the middle of the 21st century. For the relatively mild anthropogenic scenario SRES-B2 even by the end of the century there is a large area, where the increases of the permafrost active layer do not exceed 20 cm. The shift to the north of thawing depth border in the 21st century was estimated about 100–250 km.

[29] Most of model assessments of global warming, for example, the estimates of climate changes provided in the reports of the Intergovernmental Panel on Climate Change (IPCC), were made at scenarios of changes of concentration of greenhouse gases and aerosol in the atmosphere without taking into account the interrelation with natural cycles of carbon, nitrogen etc. However, the change of greenhouse gas concentration in the atmosphere due to anthropogenic emissions depends on the fluxes between the atmosphere and the ocean, land and biosphere and it is necessary to take into account their relation to climate. Thus simulations with the IAP RAS climate model with the carbon cycle at various anthropogenic scenarios (SRES A2, A1B, B2 and B1) have shown that by the end of the 21st century the concentration of CO_2 would reach 615–875 ppm in interactive simulations with additional increase of CO_2 concentration on 67–90 ppm in comparison to non-interactive simulations [*Mokhov et al.,* 2006e; *Eliseev et al.,* 2007]. (Non-interactive simulations took into account in the carbon cycle block only carbon dioxide fertilization of photosynthesis and CO_2 influence on the atmosphere-ocean interaction without the climate changes impact on terrestrial ecosystems production and CO_2 solubility in the ocean.) Therefore by the end of the 21st century the global temperature increases in the IAP RAS climate model with carbon cycle by 2.4–3.4 K relative to pre-industrial regime with additional warming by 0.3–0.4 K in comparison to non-interactive simulations.

[30] According to the assessments of changes of flows of CO_2 fluxes between the atmosphere to terrestrial ecosystems from the IAP RAS climate model simulations at different anthropogenic scenarios with or without taking into account the carbon cycle-climate interaction in the 20th century the direct (fertilization) effect prevails, increasing absorption of CO_2 by terrestrial ecosystems. In the 21st century the indirect (climate) effect dominates, reducing absorption of CO_2 by terrestrial ecosystems due to the increase of soil respiration. Analysis of changes of CO_2 fluxes from the atmosphere to the ocean has shown that the dominating growth of this flux is related to the rate of the CO_2 concentration increase in the atmosphere. From the end of the 20th century the warming influences on the CO_2 concentration growth in the atmophere due to decrease of solubility of the ocean. The increase of carbon content in the soil in non-interactive regime is related to the fertilization effect of plants. In interactive regime, starting from the middle of the 20th century, the effect of growth of soil respiration growth due to increase of temperature is dominating in changes of the soil carbon storage. According to model analysis over time intervals up to several centuries about a half of anthropogenic emissions remains in the atmosphere. The part of these emissions, remaining in the atmosphere, exceeds the one in the non-interactive regime, due to the positive feedback between the climate and carbon cycle. This part is growing with time.

[31] In [*Mokhov et al.,* 2005c] the possible changes in the 21st century of extreme climate regimes and effects of the biosphere in the regions of North Eurasia are described, in particular, for some Russian regions, obtained from simulations with the global climate model with carbon cycle and anthropogenic forcings. These model simulations take into account not only the anthropogenic influence on the climate, including biosphere, but also the influence of biospheric changes on climate characteristics. The emphasis was placed on the analysis of impact of droughts on bioproduction of terrestrial ecosystems in middle latitudes. The model simulations have predicted a growing probability of spring-summer droughts in mid-latitudes of Eurasia in the 21st century, in comparison to the 20th century [*Mokhov et al.,* 2005c]. At that the relation between the parameters of

carbon exchange and bioproduction of terrestrial ecosystems with droughts was analysed. The analysis has revealed a noticeable decline of net primary production, in the European part of Russia in particular, together with the increase of dryness index in the 20th century, whereas for the 21st century no considerable relation was noted. According to the simulations, the entire growth in the 21st century of the net primary production and net ecosystem production in the regions analyzed was related to intensification of photosynthesis caused by the growth of CO_2 concentration in the atmosphere, notwithstanding unfavorable changes of the regional climate, in particular, an increasing probability of droughts. The model results have also indicated that global warming changes the type of regional droughts. A strengthening relationship in the climate model between bioproduction and soil moisture content, accompanied by the weakening link between bioproduction and precipitation was noted.

[32] An important role in the carbon cycle along with carbon dioxide is played by methane, a greenhouse gas, whose radiative effect is 20 more active that that of CO_2. The methane cycle is exceptionally important for Russia, given the fact that a large part of its territory is covered by wetlands (the main natural source of methane emissions to the atmosphere) and permafrost (as a result of its degradation wetlands appear emitting methane). The processes in wetland ecosystems and methane cycle considered in the IAP RAS climate model increase methane concentration in the atmosphere by 10–20% in the 21st century depending on a scenario of anthropogenic forcing and a moment of time [*Eliseev et al.,* 2008]. However an interactive response to climate changes of methane emissions by wetlands doesn't entail considerable additional warming. More detailed and versatile analysis of climate effects is necessary, especially of the changes of permafrost related to climate changes, and, in particular, of the effects related to methane hydrates. Some prerequisites based on the paleodata allow us to think that in remote past considerable methane emissions to the atmosphere could play the leading role.

[33] It's worth to be mentioned in general that the data of observations not only indicate that the global warming continues, but that it accelerates. Contemporary models can adequately describe not only the basic global and regional characteristics of the Earth's climate, but their changes as well. The calculations indicate a relatively small role of variations of solar and volcanic activity in the changes of global annual-mean surface air temperature in the 21st century in comparison to anthropogenic impact (see, for example, [*Mokhov et al.,* 2006f]). According to the results obtained on the basis of numerical simulations of different climate models taking into account anthropogenic impact in the 21st century one can expect a growing number of regional extremes, including extreme cyclonic and anticyclonic activity, anomalous precipitation, leading to floods or droughts and fires.

[34] The remaining substantial uncertainty of model estimates of possible climate changes relates to a number of principal problems. First of all, there is a fundamental constraint, related to principal impossibility of exact prediction of climate changes. Possible scenarios of greenhouses gases and aerosols emissions are also uncertain. An important contemporary problem is associated with an impact assessment of the possible Gulf Stream change on the European climate (including anomalous climate regimes) under global warming. Reliable estimates with climate models require the adequate account of biogeochemical cycles, including the carbon, nitrogen and ozone cycles. A significant uncertainty exists, in particular, describing the processes of carbon exchange between the atmosphere and biosphere, land and ocean. In global climate models the methane cycle is very important. Methane is the 20 times more radiatively active greenhouse gas than CO_2. For example, very important is the assessment of the effect of growing methane emission to the atmosphere caused by global warming with permafrost degradation.

[35] Providing more adequate description of formation of climate anomalies and catastrophic phenomena requires developing, together with the global models of general circulation, of more detailed regional climate models, analyzing the functions of distribution of climate characteristics on the basis of numerical realizations at different scenarios of various external forcings and different initial conditions. On the other hand, diverse numerical experiments are also essential, set at different natural and anthropogenic scenarios with models of intermediate complexity, providing an adequate account of basic climate processes and allowing long-term numerical simulations, impossible with more detailed models of general circulation. At discussing the terms of post-Kyoto agreements together with inventory of sources and greenhouse gas emissions it would be necessary to provide estimations of climate changes accounting for interrelation with natural and anthropogenic biogeochemical cycles.

References

Akperov, M. G., M. Yu. Bardin, E. M. Volodin, G. S. Golitsyn, and I. I. Mokhov (2007), Probability distributions for cyclones and anticyclones from the NCEP/NCAR reanalysis data and the INM RAS climate model, *Izvestiya, Atmos. Oceanic Phys., 43*(6), 705.

Arnell, N., et al. (Eds.) (2001), Hydrology and water resources, in *Climate Change 2001: Impacts, Adaptation, and Vulnerability, Intergovernmental Panel on Climate Change,* edited by J. J. McCarthy, O. F. Canziani, N. A. Leary et al., p. 191, Cambridge Univ. Press, Cambridge.

Demchenko, P. F., A. A. Velichko, A. V. Eliseev, I. I. Mokhov, and V. P. Nechaev (2002), Dependence of permafrost conditions on global warming: Comparison of models, scenarios and paleoclimatic reconstructuions, *Izvestiya, Atmos. Oceanic Phys., 38*(2), 143.

Demchenko, P. F., A. V. Eliseev, M. M. Arzhanov, and I. I. Mokhov (2006), Impact of global warming rate on permafrost degradation, *Izvestiya, Atmos. Oceanic Phys., 42*(1), 32.

Eliseev, A. V., I. I. Mokhov, and A. A. Karpenko (2007), Climate and carbon cycle variations in the 20th and the 21st centuries in a model of intermediate complexity, *Izvestiya, Atmos. Oceanic Phys., 43*(1), 1.

Eliseev, A. V., I. I. Mokhov, M. M. Arzhanov, P.F. Demchenko, and S. N. Denisov (2008), Interaction of the methane cycle and processes in wetland ecosystems in a climate model of intermediate complexity, *Izvestiya, Atmos. Oceanic Phys., 44*(2), 139.

Golitsyn, G. S., I.I. Mokhov, M.G. Akperov, and M.Yu. Bardin (2007), Estimates of hydrometeorological risks and distribution functions for cyclones and anticyclones in dependence on their size and energy after reanalysis and some climate models, Prediction and Adaptation of the Society to the Extreme Climate Changes, The Plenary Lectures of the International Conference on the Problems of Hydrometeorological Security, Moscow, 26–29 September 2006, p. 53, Triada Ltd, Moscow.

Groisman, P. Ya., T. R. Karl, D. R. Easterling, R. W. Knight, P. Jamason, K. Hennessy, R. Suppiah, C. Page, J. Wibig, K. Fortuniak, V. N. Razuvaev, A. Douglas, E. Foerland, and P.-M. Zhai (1999), Changes in the probability of heavy precipitation: Important indicators of climatic change, *Climatic Change, 42,* 243, doi:10.1023/A:1005432803188.

Gruza, G. V., and E. Y. Rankova (2003), Climate variations and changes of the territory of Russia, *Izvestiya, Atmos. Oceanic Phys., 40*(2), 147.

Gruza, G. V., and E. Y. Rankova (2006), The Observed changes of modern climate, in *Possibilities of Preventing Climate Change and its Negative Consequences: the Problem of Kyoto Protocol, Material of Council-Seminar with President of RAS,* p. 60, Nauka, Moscow.

Houghton, J. T., et al. (Eds.) (2001), *Climate Change 2001: The Scientific Basis, Intergovernmental Panel on Climate Change,* 881 pp., Cambridge Univ. Press, Cambridge.

Khon, V. Ch. (2007), Estimate methods of hydrological regime changes under the influence of climate changes, in *Hydrological Impact of Climate Change,* p. 184, IWEP SB RAS, Novosibirsk.

Khon, V. Ch., and I. I. Mokhov (2006), Model estimates for the sensitivity of atmospheric centers of action to global climate changes, *Izvestiya, Atmos. Oceanic Phys., 42*(6), 688.

Khon, V. Ch., I. I. Mokhov, E. Roeckner, and V. A. Semenov (2007), Regional changes of precipitation characteristics in Northern Eurasia from simulations with global climate models, *Glob. Planet. Change, 57,* 118, doi:10.1016/j.gloplacha.2006.11.006.

Kiktev, D. B., D. M. Sexton, L. V. Alexander, and K. Folland (2002), Trends in fields of intraannual extrema for precipitation and surface air temperature in the second half of the 20th century, *Russ. Meteorol. Hydrol.,* no. 11, 13.

Meleshko, V. P., G. S. Golitsyn, V. A. Govorkova, P. F. Demchenko, A. V. Eliseev, V. M. Katsov, S. P. Malevsky-Malevich, I. I. Mokhov, E. D. Nadezhdina, V. A. Semenov, P. V. Sporyshev, and V. Ch. Khon (2004), Anthropogenic climate changes in Russia in the 21st century: An ensemble of climate model projections, *Russ. Meteorol. Hydrol.,* no. 4, 38.

Mokhov, I. I. (2006a), Model estimates of possible climate changes in the 21st century in comparison to climate changes in the past and present, in *Possibilities of Preventing Climate Change and its Negative Consequences: The Problem of Kyoto Protocol, Material of Council-Seminar with President of RAS,* p. 75, Nauka, Moscow.

Mokhov, I. I. (2006b), Action as an integral characteristic of climatic structures: Estimates for atmospheric blockings, *Doklady Earth Sci., 409*(3), 925.

Mokhov, I. I. (2007a), Possible changes of precipitation and river runoff in Russian regions in the 21st century from model simulations, in *Water Resources of Land Under Changing Climate,* p. 46, Nauka, St. Petersburg.

Mokhov, I. I. (2007b), Estimates of possible regional hydrological regime changes in the 21st century based on global climate models, in *Hydrological Impact of Climate Change,* p. 140, IWEP SB RAS, Novosibirsk.

Mokhov, I. I., and V. Ch. Khon (2005), Interannual variability and long-term tendencies of change in atmospheric centers of action in the Northern Hemisphere: Analysis of Observational data, *Izvestiya, Atmos. Oceanic Phys., 41*(6), 657.

Mokhov, I. I., and D. A. Smirnov (2008), Relationships between global surface temperature, carbon dioxide atmospheric content, solar and volcanic activity during the last 150 years, in *Research Activities in Atmospheric and Oceanic Modeling, Rep. 38,* edited by J. Cote, p. 2.15, World Climate Research Programme, Geneva.

Mokhov, I. I., V. A. Semenov, and V. Ch. Khon (2003), Estimates of possible regional hydrologic regime changes in the 21st century based on global climate models, *Izvestiya, Atmos. Oceanic Phys., 39*(2), 130.

Mokhov, I. I., E. Roeckner, V. A. Semenov, and V. Ch. Khon (2005a), Extreme precipitation regimes in Northern Eurasia in the 20th century and their possible changes in the 21st century, *Doklady Earth Sci., 402*(6), 767.

Mokhov, I. I., A. V. Eliseev, P. F. Demchenko, V. Ch. Khon, M. G. Akperov, M. M. Arzhanov, A. A. Karpenko, V. A. Tikhonov, A. V. Chernokulsky, and E. V. Sigaeva (2005b), Climate changes and their assessment based on the IAP RAS global model simulations, *Doklady Earth Sci., 402*(2), 591.

Mokhov, I. I., J.-L. Dufresne, H. Le Treut, V. A. Tikhonov, and A. V. Chernokulsky (2005c), Regional changes of drought regimes and terrestrial biospheric production in Northern Eurasia from simulations of global climate model with carbon cycle, *Doklady Earth Sci., 405*(9), 1414.

Mokhov, I. I., A. A. Karpenko, and P. A. Stott (2006a), Highest rates of regional climate warming over the last decades and assessment of the role of natural and anthropogenic factors, *Doklady Earth Sci., 406*(1), 158.

Mokhov, I. I., V. A. Bezverkhny, A. V. Eliseev, and A. A. Karpenko (2006b), Interrelation between variations in the global surface air temperature and solar activity based on observations and reconstructions, *Doklady Earth Sci., 409*(1), 805.

Mokhov, I. I., E. Roeckner, V. A. Semenov, and V. Ch. Khon (2006c), Possible regional changes in precipitation regimes in Northern Eurasia in the 21st century, *Water Resources, 33*(6), 702.

Mokhov, I. I., A. V. Chernokulsky, and I. M. Shkolnik (2006d), Regional model assessments of fire risks under global climate changes, *Doklady Earth Sci., 411*(9), 1485.

Mokhov, I. I., A. V. Eliseev, and A. A. Karpenko (2006e), Sensitivity to anthropogenic forcing of the IAP RAS Global Climate Model with an interactive carbon cycle, *Doklady Earth Sci., 407*(3), 424.

Mokhov, I. I., V. A. Bezverkhny, A. V. Eliseev, and A. A. Karpenko (2006f), Model estimates of global climatic changes in the 21st century with account for different variation scenarios of solar activity, *Doklady Earth Sci., 411*(8), 1327.

Semenov, V., and L. Bengtsson (2002), Secular trends in daily precipitation characteristics: Greenhouse gas simulation with a coupled AOGCM, *Clim. Dyn., 19,* 123, doi:10.1007/s00382-001-0218-4.

Solomon, S., et al. (Eds.) (2007), *Climate Change 2007: The Physical Science Basis,* 996 pp., Cambridge University Press, Cambridge/New York.

I. I. Mokhov, A. M. Obukhov Institute of Atmospheric Physics RAS (mokhov@ifaran.ru)