Contemporary climate changes: anomalies and trends

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Abstract. The tendencies of contemporary global and regional climate changes are characterized using long-term data and model simulations in comparison with paleoclimatic reconstructions. The features of climate change in the Arctic and in different Russian regions are noted. The processes that contribute to the climate “nervousness” are considered. The roles of natural and anthropogenic factors in climate change are determined, as well as the ability of numerical models to adequately assess climate change. Global and regional climate trends and their consequences in the 21st century are assessed.

Recent decades are characterized by significant climate changes that are noticeably manifested in the frequency and intensity of extreme regional events [1-3]. On the background of general warming, an increase in climate variability (“nervousness”) is observed, as was noted by A.M. Obukhov. In 2012-2017 the number of anomalous meteorological phenomena in Russian regions was almost three times higher than that in 1998-2002, and in 2017 there were almost 4 times more of those than in 2000 - see Fig. 1 (http://www.meteorf.ru/). The highest frequency of extreme events (especially those related to hydrological processes) is observed during the warmer months of the year. By examining extreme events of recent decades, it can be assumed that the risk of extreme regional conditions similar to those observed in spring 2017 and 2018 in Moscow region with squalls of wind with storm and hurricane strength [4], is significant for the Russian regions.

Figure 1. Changes in the number of dangerous meteorological phenomena in Russia since the end of the 20th century.

In [5], after conducting empirical and model analysis of climatic variability, it was stated that changes in variance of climatic variables strongly depend on the hydrological cycle characteristics. Under global
warming, with the increase of the atmospheric moisture capacity and with the change of the transfer of water vapor and latent heat to high latitudes, the weakening of zonal tropospheric mixing promotes more heterogeneous distribution of precipitation and latent heat with the increase of regional climatic variability. In particular, the trend of increase in variance of the hemispheric surface air temperature and in variance of the difference of surface air temperatures between equatorial and polar latitudes under hemispheric warming with decreasing the equator-pole temperature difference was noted.

The general increase in global surface air temperature (GSAT) from observations since the mid-19th century was accompanied by periods of its more rapid growth (from the 1910s to the 1930s and from the second half of the 1970s to the 2000s) and a decrease (from 1940s until the mid-1970s). By the beginning of the 21st century, the warming trend has decreased, at the same time the GSAT of the recent years (2017, 2016, 2015, 2014) were among the highest in 17 decades. One of key contemporary problems is the quantitative contribution assessment of the natural and anthropogenic factors to the GSAT changes [1-3,6-8]. According to [1], more than a half of the GSAT increase since the middle of the 20th century is associated with anthropogenic increase in the atmospheric concentration of greenhouse gases.

The significant anthropogenic factor for long-term changes is an increase in the content of greenhouse gases in the atmosphere, primarily of carbon dioxide. In recent years, the CO₂ content in the Earth's atmosphere has exceeded the milestone of 400 ppm, which exceeds pre-industrial level by more than 40%. Comparison of these concentrations with paleoreconstructions indicates current CO₂ content to be the highest of at least the last 800 thousand years.

Model simulations indicate fundamental differences in stratosphere and mesosphere temperature changes associated with various natural (due to variations in solar radiation and volcanic activity, in particular) and anthropogenic causes of climate changes. The general cooling of the strato- and mesosphere, revealed by the results of various observations under global surface air warming in recent decades, characterizes the potential role of anthropogenic mechanisms of global climate changes. The strongest cooling in the last half century has been observed in the upper mesosphere (about 90 km, at mesopause). Nonlinear changes in mesopause temperatures with an abrupt decrease in the 1970s are taking place (synchronous with the shift in surface climatic features associated with El-Niño phenomena) with a subsequent slowdown of the cooling rate [9]. Considering significant negative correlation of temperature variations in near the mesopause with the surface air temperature for the last 6 decades, the cross-wavelet analysis did not reveal significant coherence between corresponding long-term temperature variations. Their significant coherence can only be obtained by examining substantially longer periods of observations.

The analysis of observations for surface air temperatures from the mid-19th century, conducted in [6], indicates the determining role of CO₂ content in the long-term (on a centennial time scale) changes in global and Arctic climate. The contribution of CO₂ content to the variance of global annual-mean temperature was estimated to be more than ¾. The corresponding contribution of the 60-year mode was obtained about 5%, and contribution of all other factors was estimated about 1/6.

In [11], the conditions for the influence of the 60-year mode were obtained considering hundred-year trend of warming, including the possible decrease of the warming rate or even some local cooling over the next two decades followed by more rapid warming on regional and global scales. In the simplest case of harmonic fluctuations for temperature $T(t)$ with a period $T_0$ (of about 60 years) and amplitude $\Delta T$ considering a secular linear trend $(dT/dt)_c$, the absence of a time interval with cooling is possible under the condition

$$\left(\frac{dT}{dt}\right)_c \left(\frac{2\pi \Delta T}{T_0}\right)^{-1} \geq 1$$

According to estimates obtained in [11] the decrease of the warming rate and even some local cooling over the next two decades are possible, followed by a more rapid warming both in the Arctic and in the Northern Hemisphere (globally).

For relatively short-term (interannual and interdecadal) changes, the temperature variations between the extremes of the 11-year solar cycle usually do not exceed 0.1–0.2 K [12]. The uncertainty of these effects is the highest in Arctic latitudes. (It should be also noted that in polar latitudes there is the greatest uncertainty in the cloud characteristics determination [13-15]). Short-term effects of variations in solar radiation are significant, but not crucial for the last decades.
In [7,8], quantitative estimates of contributions of natural and anthropogenic factors are made, in particular, of the contribution of greenhouse gases radiative forcing and AMO to GSAT trends in different latitudinal zones for different time intervals. Based on the observational data from the mid-19th century, the characteristics of various factors' effects on temperature changes (“Wiener–Granger causality”) were obtained, using three-component autoregressive models. At relatively short time scales of 15–30 years, AMO’s contribution is comparable in magnitude with that of greenhouse gases and could even exceed it, while at scales of about six decades or more AMO’s contribution to the GSAT trend is insignificant.

According to the obtained results, the contribution of the AMO at time scales of 15–30 years reaches ± 0.1 K per decade, and at time scales of about 60 years there is no significant contribution of the AMO to the trend of GSAT. The contributions of AMO and of greenhouse gases to the 15-year trend of GSAT in recent years are close in magnitude, with the contribution of AMO to the trend of GSAT at intervals of 15-30 years possibly to be even greater than the contribution of variations in atmospheric concentration of greenhouse gases (in particular, during 1920–1950). In order to come to reliable conclusions about the role of greenhouse gases in sufficiently long-term temperature changes, it is necessary to use time intervals of at least half a century. In recent decades, according to the estimates obtained, the ratio of the contribution of greenhouse gases to temperature trends to the contribution of AMO to these trends is greater for the GSAT and for the tropics, and less for middle and high latitudes [7,8].

With strongest climatic anomalies and warming trends in high latitudes [11,16] the most explicit manifestation of warming in recent decades is a very rapid degradation of sea ice in the Arctic basin. Changes in the sea ice regime affect ocean-atmosphere interaction, atmospheric circulation and formation of regional climate anomalies not only in polar latitudes, but also outside the Arctic region [17–19], for example, in some Russian regions. In particular, this was manifested in the formation of abnormally cold winters in recent years in different regions of the Northern Hemisphere. The occurrence of such regional seasonal anomalies not only does not contradict the trend of global warming, but also confirms the results of model simulations [20,21] with an increase in their probability (especially in winter over the continents) with global warming. The tendency of reduction of the Antarctic sea ice extent during recent years is also important to note.

In [22–24], a general increase in wave activity in the Arctic basin was noted, including an increase in the formation of strong waves in various water reservoirs, according to model simulations for the 21st century. This growth apparently relates to the increase in open-water area that should lead to longer wave-development fetches. At the same time, an increase in the frequency of occurrence of days with strong winds and intense waves is detected in Russian Arctic seas. (This tendency contributes to increased coastal erosion in the Arctic basin, and therefore is associated with permafrost degradation. Increased sea swell can also contribute to an increase in the intensity of infrasonic radiation.) The opposite trend with a general weakening of the sea waves was revealed in the Barents Sea basin, which is associated with a regional decrease in wind speed. The possibility of predicted in [22–24] spatially heterogeneous changes in the wind-wave regime in the Arctic regions in the first half of the 21st century for regional model calculations, taking into account anthropogenic influences, was later confirmed in [25] using satellite data and reanalysis for recent years. Until 2006, there was a trend of wave heights and wind speed increase for all seas of Russian Arctic. And after 2007, the trend of increasing wave heights reversed for Barents and Kara seas [26].

The described example of new model results being confirmed by observations proves not only the ability of modern models to adequately reproduce global and regional climatic regimes and their changes, but also the potential to identify new effects that are not manifested or seem insignificant under the current climatic regime, but that can appear in case of more intense climate changes. Detection of possible qualitative transitions (“shifts”) during climate change is important for assessing critical changes, above which not only a change in the structure of the climate system at the regional and global scales is possible, but also a transition to irreversible changes.

Under conditions of sufficiently large uncertainties of model simulation results, climatic changes can be assessed more reliably and significantly by ensemble model calculations. Moreover, in climate studies, quite often the results of simulations with an ensemble of all analyzed models correspond better to observational data, rather than each individual model does. In this case, the estimates depend on the ensemble statistics and the criteria for the compliance of the model simulations with real data. In order to obtain more accurate estimates, it is possible to select a sub-ensemble of models that better fit the actual data [27–29] and to use the Bayesian approach [30].

The best models are able to adequately reproduce not only regional features of climatic regimes, but also their current variability and trends [26]. This is evidenced, in particular, in the results of model estimates of changes in the navigation period for the Northern Sea Route obtained in [27–30] compared
with the satellite data for the last decades. Moreover, according to the obtained model estimates considering
general warming and an increase in the navigation period on the Northern Sea Route in the 21st century,
with sufficiently large interannual variability in the coming decades in the first half of the century, one can
expect weakening of the growth trend of the navigation period duration and even local manifestations of its
decrease.

Changes in the vertical temperature structure of the atmosphere and in its static stability under global
warming are associated with changes in convective processes in the atmosphere, cloud patterns, and vortex-
wave activity. The extratropical cyclogenesis is associated with baroclinic instability and depends both on
the meridional temperature gradient and on the lapse rate. Climate feedback through the vertical
temperature gradient in the troposphere significantly influences climate sensitivity to various influences
[31,32].

Figure 2 shows the latitudinal dependences of the lapse rate estimates $\gamma$ in the troposphere normalized
to the corresponding average values for the Northern Hemisphere (NH), of the $d\gamma/dT$ parameter that
characterizes sensitivity of $\gamma$ to the change in the surface air temperature $T$ and of the parameter $p=\gamma$
$(d\gamma/dT)\delta T$, characterizing the relative role of variations in the lapse rate in the troposphere at different
latitudes in the interannual variability, characterized by the standard deviation $\delta T$ from reanalysis data for
the period 1979-2014 [33]. The parameter $d\gamma/dT$ was estimated from the annual data using linear regression
$\gamma$ on $T$. The values of the parameter $p$ in the Arctic latitudes are 4 times greater than they are in the Northern
Hemisphere and much greater than they are for tropical latitudes. A general positive correlation of $\gamma$ with
the surface temperature $T$ indicates corresponding positive climate feedback.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Latitudinal dependence of the estimates of the vertical temperature gradient in the troposphere,
normalized to the corresponding average values for the Northern Hemisphere (NH), the parameter $d\gamma/dT$,
which characterizes the sensitivity $\gamma$ to changes in the surface temperature $T$, and the parameter $p=\gamma$
$(d\gamma/dT)\delta T$, which characterizes the relative role of variations in the vertical temperature stratification in
the troposphere at different latitudes in the interannual variability $\delta T$, from reanalysis data for the period
1979-2014.}
\end{figure}

The characteristics shown in Fig. 2 contribute to the weakening of the atmospheric static stability
and to the strengthening of convective processes during warming with increasing frequency, intensity and
duration of extreme weather and climate phenomena. The conditions with the increased atmospheric
moisture capacity (in accordance with the Clausius-Clapeyron equation) increase the risk of intense
atmospheric vortices formation [34].

Due to the intensification of convective processes, a tendency for the growth of convective clouds,
in particular for Northern Eurasia [35,36], and for the frequency of rainfall is noted. In [37], the estimates
of the tornado risk growth in the North Eurasian regions based on reanalysis data for the last decades were
obtained (see also [38]). Appropriate estimates were obtained for possible climate changes in the 21st century from simulations with the ensemble of global climate models [37]. The increase in the frequency of conditions contributing to the tornadogenesis in the North Eurasian regions is revealed. The most significant increase was obtained for the Far East and the Black Sea region. Extremely high sea surface temperatures [39] contribute to the formation of powerful convective processes with extreme precipitation. For instance, the record flooding in the Amur River basin in 2013 was associated with the extremely high surface temperature of the Pacific Ocean [40].

As atmospheric moisture capacity increases with global warming, higher risks of extreme regional precipitation are expected. Figure 3 shows model estimates of seasonal changes in precipitation characteristics in the Moscow region (50–60°N, 30–45°E) for possible climatic changes in the 21st century: total precipitation (mm/day), intensity (mm/day), probabilities (the number of days with precipitation) (see [41–44]). In case of zonal transfer weakening in the mid-latitude troposphere the moisture is not so efficiently transported in the atmosphere into the inland regions. (Zonal wind speed in the troposphere may also increase under global warming with stratospheric cooling due to the intensification of subtropical jet streams.) The lack of precipitation in the inland regions lead to the formation of droughts in the summer. The weakening of the meridional temperature gradient and midlatitudinal zonal circulation in the troposphere contribute to an increase in the probability of meridional breakthroughs of cold polar air to middle latitudes or warm and humid air from low latitudes with the formation of corresponding temperature and precipitation anomalies.

In [45], the analysis of the features of the probability density functions (PDF) for key atmospheric variables has been carried out. Using long-term reanalysis data for the last decades, the effect of non-Gaussian statistics of atmospheric variables on extreme monthly anomalies has been estimated. The revealed deviations of probability distribution from the normal distribution significantly increase the probability of occurrence of large in absolute magnitude atmospheric anomalies compared with the case of Gaussian PDFs.

Intraseasonal variability of the surface temperature analysis from long-term observational data reveals the multimodal features of the PDF. This is facilitated by various mechanisms, in particular, by blocking of zonal transfer in middle latitudes and formation of blocking anticyclones (blockings) and stationary Rossby waves; and in transitional (spring, autumn) seasons, by abrupt changes in surface albedo during the formation and melting of snow cover [46–50].

In [47], analytical conditions for the formation of a bimodal PDF for zonal temperature variations were obtained by analyzing the Fokker-Planck equation obtained using the stochastic energy-balance climate model with a nonlinear albedo-temperature dependence. In [49], a similar mechanism of possible
polymodal regimes formation in transitional seasons was proposed to explain the anomalous temperature regimes in spring 2017, particularly in the Russian regions (see also [50]). Explicit regular anomalies of the autumn transitional regimes are the phenomena of recurrent warming, the so-called “Indian summer”. In [46], the explanation is given for the formation of this phenomenon by the stationing of Rossby waves using data obtained during the First Global Experiment.

Changes in temperature \((T)\) and circulation \((U)\) regimes cause changes in the modes of Rossby waves, as well as in the conditions for their stationing with equal zonal wind speed \(U\) speed of Rossby wave \(U\),

\[
\frac{dU}{dt} U^{-1} = -2 \frac{dm}{dt} m^{-1},
\]

where \(m\) is the wave number. If \(dU/dT < 0\) then \(dm/dT > 0\). This means that the weakening of the zonal flow during warming contributes to the stationary Rossby waves with a higher wave number. Considering the ongoing climate change, manifestations of the effects of spatial resonance of planetary waves can be expected [46,48,51], along with changes in the conditions of stationing of Rossby waves.

The strongest regional weather and climate anomalies that depend on global climate change are associated with blockings, including anomalous heat in the summer of 2010 in the European territory of Russia, extreme flooding in the Amur basin, anomalous frost of recent years [17,34,52,53]. The formation of atmospheric blocking contributes to increased climate variability. In case of expansion of their lifetime in the atmosphere with a weak zonal transfer and mixing, or with growing blocking density, during increasing the zonal flow in the mid-latitude troposphere, intensification of climate anomalies associated with blocking situations in summer and frost in winter should be expected [54]. There is a significant risk of increased regional blocking activity with significant consequences if global warming continues [1,20,22,56]. At the same time, the formation of atmospheric blocking, their changes and consequences are characterized by essentially non-linear effects. As described in [52], blocking in the troposphere helps to compensate for the effect of jet stream intensification by angular momentum.

Among the Russian regions with the strongest warming in the summer during the last decades with a manifestation of a tendency to decrease summer precipitation is the region of Lake Baikal. At the same time, the extremely high temperature and precipitation deficit in the Lake Baikal basin were observed in the summer of 2015 during the development of the El-Niño phenomenon. In [57], a significant coherence of summer precipitation in the basin of Lake Baikal with El-Nino phenomena over the past decades has been established. Those regional climate anomalies and trends contribute to the formation of negative anomalies and trends for water balance in the Lake Baikal basin. According to [58], with continued warming in the 21st century, according to model estimates the variability of surface air temperature and precipitation in the spring and summer months increases with the weakening of their relationship in mid-latitude Russian regions.

The strongest interannual variations of GSAT, which are manifested in climatic variations in different latitudes, including in Russian regions, are associated with the El-Nino phenomena [19,59-64] quantitative estimates of the probability of regional climatic anomalies at different phase transitions for El-Niño phenomena are obtained. According to long-term data from the end of the 19th century the greatest risk of extremely high surface temperature and drought conditions in spring-summer months was revealed during the transition from the El Niño phase at the beginning of the year to the La-Niña phase at the end of the year (as in 2010) for regions of the European territory of Russia and with the continuation of the El-Nino phase throughout the year (as in 2015) for the regions of the Asian territory of Russia. Statistically significant connection with El-Nino phenomena was found for the hydrological conditions in the Caspian Sea basin and its level in [59].

Regional atmosphere composition anomalies are associated with regional climate anomalies [65-70]. In particular, quasi-stationary anticyclonic conditions in the atmosphere contribute to the formation of anomalous regional atmospheric components and pollutants. As a result, regional environmental consequences are possible due to the formation of ozone “mini-holes” with anomalies of the intensity of biologically active solar radiation, together with the formation of anomalous transboundary transport of, in particular, the products of burning forest fires. An increment in the probability of long-lived blockings with a quasi-stationary anticyclonic regime with general warming [56] increases the risk of such regional anomalies.

Significant climatic anomalies and socio-economic consequences are associated with the most powerful tropical cyclones - typhoons (hurricanes) [34]. In recent years, powerful cyclones, including those transformed from tropical in the North Atlantic and in the north-western part of the Pacific Ocean in the
Northern Hemisphere [62], have been increasingly observed in extratropical latitudes. Because of the global warming trend, an increase in the number of intense cyclones in the warmer and more moisture troposphere should be expected. Analysis of data since 1970 revealed statistically significant positive trends in the number of extratropical cyclones, transformed from tropical, for the Northern Hemisphere and for the Earth as a whole. In the Northern Hemisphere, a significant growth trend in the likelihood of transformation events has been identified for the northwestern Pacific.

The climatic anomalies of recent years testify not only to an increase in the risk of extreme regional events, but also to the manifestation of new phenomena that characterize reaching a certain critical level of the changes taking place. For example, in recent years, the formation of craters on Yamal (for the first time in 2014) and adjacent regions [71-73] has been revealed. In [72-73], the formation of such craters is associated with the decomposition of shallow-bed methane hydrates with gas emissions into the atmosphere in regions of permafrost with ongoing warming. According to [72-73], the formation of shallow methane hydrates was possible under high pressure of the ice sheet existing in the marked regions tens of thousands years ago. The fact that craters like the one in Yamal are currently being formed suggests that modern climate warming can be not only comparable to the warming of the Holocene optimum about 6 thousand years ago, but also surpass it, at least at the regional scale. In general, this agrees with the estimates [74] for the Holocene. Assessments of crater formation in North America regions were also made in [73].

To sum up, the necessity of change of many criteria of risk assessments and potential benefits associated with climate change should be considered, and possible changes and their consequences should be strategically evaluated, including taking into account the increased probability of abnormal regional regimes.

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References

[1] Stocker T F, Qin D, Plattner G-K et al (eds) 2013 IPCC 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge/New York. Cambridge University Press pp 1535

[2] Second Assessment Report of Roshydromet on Climate Change and Its Consequences on the Territory of the Russian Federation (Moscow. Roshydromet 2014) pp 1008 (in Russian)

[3] Mokhov I I Russian climate studies in 2011-2014 2017 Izvestiya, Atmos. Oceanic Phys. 53 (5) 550-63

[4] Mokhov I I, Timazhev A V, Yushkov V P 2018 Squalls with a hurricane wind in Moscow Research Activities in Atmospheric and Oceanic Modelling E Astakhova (ed) Rep No 48 WCRP Rep No 15/2018 S 2 pp 21-22

[5] Arsky A A, Mokhov I I and Petukhov V K 1989 Modeling of trends in the characteristics of variability of the thermodynamic regime of the Earth climatic system Izvestiya, Atmos. Oceanic Phys. (Izvestiya A. N. SSSR Fiz. Atmos.) 25 (1) 3-13

[6] Gruza G V and Rankova E Ya 2012 Observed and expected climate changes over Russia: surface air temperature Obninsk RIHMI-WDC 194 (in Russian)

[7] Mokhov I I and Smirnov D A 2018 Estimating the contributions of the Atlantic Multidecadal Oscillation and variations in the atmospheric concentration of greenhouse gases to surface air temperature trends from Observations Doklady Earth Sci. 480 (1) 602-6

[8] Mokhov I I and Smirnov D A 2018 Contribution of greenhouse gas radiative forcing and Atlantic Multidecadal Oscillation to surface air temperature trends Russ. Meteorol. Hydrol. 43 (9) 557-64

[9] Mokhov I I and Semenov A I 2014 Nonlinear temperature changes in the atmospheric mesopause region of the atmosphere against the background of global climate changes, 1960-2012 Doklady Earth Sci. 357 (5) 687-9

[10] Mokhov I I, Semenov A I, Volodin E M and Dembitskaya M A 2017 Changes of cooling near mesopause under global warming from observations and model simulations Izvestiya, Atmos. Oceanic Phys. 53 (4) 383-91

[11] Mokhov I I 2015 Contemporary climate changes in the Arctic Herald Russ. Acad. Sci. 85 (3) 265-71
[12] Tung K K, Zho J and Camp C D 2008 Constraining model transient climate response using independent observations of solar cycle forcing and response Geophys. Res. Lett. 35 № 17 L17707

[13] Mokhov I I and Schlesinger M E 1993 Analysis of global cloudiness. 1. Comparison of Meteor, Nimbus 7, and International Satellite Cloud Climatology Project (ISCCP) satellite data J. Geophys. Res. 98 No D7 12849-68

[14] Mokhov I I and Schlesinger M E 1994 Analysis of global cloudiness. 2. Comparison of ground-based and satellite-based cloud climatologies J. Geophys. Res. 99 No D8 17045-65

[15] Chernokulsky A V and Mokhov I I 2012 Climatology of total cloudiness in the Arctic: An intercomparison of observations and reanalyses Advances in Meteorology 2012 15

[16] Alekseev G V 2014 Arctic dimension of global warming Led i Sneg 53 (2) 53-68 (in Russian)

[17] Mokhov I I and Semenov V A 2016 Weather and climate anomalies in Russian regions related to global climate change Russ. Meteorol. Hydrol. 41 (2) 84-92

[18] Mokhov I I and Parfenova M R Relationship between the Caspian Sea level and the Arctic sea ice extent 2018 Research Activities in Atmospheric and Oceanic Modelling E Astakhova (ed) Rep No 48 WCRP Rep No 15/2018 S 2 17-18

[19] Mokhov I I and Parfenova M R 2018 Link of the Barents Sea ice extent with El-Nino phenomena Research Activities in Atmospheric and Oceanic Modelling E Astakhova (ed) Rep No 48 WCRP Rep No 15/2018 S 2 19-20

[20] Lupo A R, Oglesby R J and Mokhov I I 1997 Climatological features of blocking anticyclones: a study of Northern Hemisphere CCM1 model blocking events in present-day and double CO2 concentration atmospheres Clim. Dyn. 13 181-9

[21] Mokhov I I, Timazhev A V and Lupo A R 2014 Changes in atmospheric blocking characteristics within Euro-Atlantic region and Northern Hemisphere as a whole in the 21st century from model simulations using RCP anthropogenic scenarios Glob. Planet. Change 122 265-70

[22] Mokhov I I, Akperov M G, Prokof'eva M A, Timazhev A V, Lupo A R and Le Treut H 2013 Blockings in the Northern Hemisphere and Euro-Atlantic region: Estimates of changes from reanalysis data and model simulations Doklady Earth Sci. 449(2) 430-33

[23] Khon V C, Mokhov I I and Pogarskii F A 2013 Estimating changes of wind-wave activity in the arctic ocean in the 21st century using the regional climate model Doklady Earth Sci. 452 (2) 1027-29

[24] Khon V, Mokhov I I, Pogarskii F, Babanin A, Dethloff K, Rinke A and Matthes H 2014 Wave heights in the 21st century Arctic Ocean simulated with a regional climate model Geophys. Res. Lett. 41(8) 2956-61

[25] Liu Q, Babanin A V, Zieger S et al 2016 Wind and wave climate in the Arctic Ocean as observed by altimeters J. Climate 29 7957-75

[26] Mokhov I I 2018 Assessment of the ability of contemporary climate models to assess adequately the risk of possible regional anomalies and trends Doklady Earth Sci. 479 (2) 482-85

[27] Mokhov I I and Khon V C 2015 The duration of the navigation period and changes for the Northern Sea Route: model estimates Arctic: Ecology and Economy 2 (18) 88-95

[28] Mokhov I I, Khon V C and Prokof'eva M A 2016 New model estimates of changes in the duration of the navigation period for the Northern Sea Route in the 21st century Doklady Earth Sci. 468 (2) 641-45

[29] Khon V C, Mokhov I I and Semenov V A 2017 Transit navigation through Northern Sea Route from satellite data and CMIP5 simulations Environ. Res. Lett. 12 024010

[30] Kibanova O V, Eliseev AV, Mokhov I I and Khon V C 2018 Variations in the duration of the navigation period along the Northern Sea Route in the 21st century based on simulations with an ensemble of climatic models: Bayesian estimates Doklady Earth Sci. 481 (1) 907-11

[31] Mokhov I I 1983 Vertical temperature lapse rate in the troposphere and its relation to the surface temperature by empirical data Izvestiya, Atmos. Oceanic Phys. (Izv. A. N. SSSR Fiz. Atmos. Ok.) 19 (9) 913-19

[32] Mokhov I I, Akperov M G 2006 Tropospheric lapse rate and its relation to surface temperature from reanalysis data Izvestiya, Atmos. Oceanic Phys. 42 (4) 430-38

[33] Mokhov I I, Akperov M G and Dembitskaya M A 2016 Lapse-rate feedback assessment from reanalysis data Research Activities in Atmospheric and Oceanic Modelling E Astakhova (ed) WCRP Rep No 15/2016 S 2 pp 7-8

[34] Mokhov I I, Kurgansky M V and Chkhetiani O G Intense atmospheric aortices and their dynamics 2018 Mokhov I I, Kurgansky M V and Chkhetiani O G (eds) Moscow GEOS 482 pp (in Russian)
[35] Sun B, Groisman P Ya and Mokhov I I 2001 Recent changes in cloud type frequency and inferred increases in convection over the United States and the former USSR J. Climate 2001 14 1864-80

[36] Chernokulsky A V, Bulygina O N and Mokhov I I 2011 Recent variations of cloudiness over Russia from surface daytime observations Environ. Res. Let. 6 № 3 pp 035202

[37] Chernokulsky A V, Kurgansky M V, Mokhov I I 2017 Analysis of changes in tornadogenesis conditions over Northern Eurasia based on a simple index of atmospheric convective instability Doklady Earth Sci. 477 (2) 1504-09

[38] Mokhov I I, Chernokulsky A V and Semenov V A 1998 Multiple intraseasonal temperature regimes and their evolution in the IAP RAS climate model Izvestiya, Atmos. Oceanic Phys. (Izvestiya A. N. Fiz. Atmos. Ok.) 34 (2) 163-71

[39] Mokhov I I 2011 Specific features of the 2010 summer heat formation in the European territory of Russia in the context of general climate changes and climate anomalies Izvestiya, Atmos. Oceanic Phys. 47(6) 653-60

[40] Lupo A R, Mokhov I I, Akperov M G, Chernokulsky A V and Athar H 2012 A dynamic analysis of the role of the planetary and synoptic scale in the summer of 2010 blocking episodes over the European part of Russia Adv. Meteorol. 2012 11

[41] Mokhov I I and Petukhov V K 1997 Blockings and tendencies of their change Doklady Earth Sci. (Doklady A. N.) 357 (5) 687–89

[42] Mokhov I I 2006 Action as an integral characteristic of climatic structures: estimates for atmospheric blockings Doklady Earth Sci. 409A (6) 925–28

[43] Mokhov I I and Timazhev A V 2015 Model assessment of possible changes of atmospheric blockings in the Northern Hemisphere under RCP scenarios of anthropogenic forcings Doklady Earth Sci. 460 (1) 63-67
[57] Mokhov I I and Timazhev A V 2016 Climate anomalies and tendencies of change in Lake Baikal basin Research Activities in Atmospheric and Oceanic Modelling E Astakhova (ed) WCRP Rep No 15/2016 S 2 pp 9–10
[58] Mokhov I I and Timazhev A V 2018 Precipitation-temperature relationship in spring-summer for Eurasian regions: Model projections Research Activities in Atmospheric and Oceanic Modelling E Astakhova (ed) Rep No 48.2018 WCRP Rep No 15/2018 S 7 pp 07-08
[59] Arpe K, Bengtsson L, Golitsyn G S, Mokhov I I, Semenov V A and Sporyshev P V 1999 Analysis and modeling of hydrological regime variations in the Caspian Sea basin Doklady Earth Sci. 366 (2) 248-52
[60] Wiedenmann J M, Lupo A R, Mokhov I I and Tikhonova E V 2002 The climatology of blocking anticyclones for the Northern and Southern Hemispheres: Block intensity as a Diagnostic J. Climate 15 3459-73
[61] Mokhov I I and Timazhev A V 2013 Climatic anomalies in Eurasia from El-Nino/La-Nina effects Doklady Earth Sci. 453 (1) 1141-44
[62] Mokhov I I, Dobryshman E M and Makarova M E 2014 Transformation of tropical cyclones into extratropical: The tendencies of 1970-2012 Doklady Earth Sci. 454 (1) 59–63
[63] Mokhov I I and Timazhev A V 2015 Assessment of the predictability of climate anomalies in connection with El Nino phenomena Doklady Earth Sci. 464 (2) 1089-93
[64] Mokhov I I and Timazhev A V 2017 Assessing the probability of El-Nino-related weather and climate anomalies in Russian regions Russ. Meteorol. Hydrol. 42 (10) 635-43
[65] Sitnov S A and Mokhov I I 2015 Ozone mini-hole formation under prolonged blocking anticyclone conditions in the atmosphere over European Russia in summer 2010 Doklady Earth Sci. 460 (1) 41-45
[66] Sitnov S A and Mokhov I I 2016 Satellite-derived peculiarities of total ozone field under atmospheric blocking conditions over the European part of Russia in summer 2010 Russ. Meteorol. Hydrol. 41 (1) 28-36
[67] Sitnov S A and Mokhov I I 2017 Anomalous transboundary transport of the products of biomass burning from North American wildfires to Northern Eurasia Doklady Earth Sci. 475 (1) 832-35
[68] Sitnov S A, Mokhov I I and Gorchakov G I 2017 The link between smoke blanketing of European Russia in summer 2016, Siberian wildfires and anomalies of large-scale atmospheric circulation Doklady Earth Sci. 472 (2) 190-95
[69] Sitnov S A, Mokhov I I, Gorchakov G I and Dzhola AV 2017 Smoke haze over the European part of Russia in the summer of 2016: A link to wildfires in Siberia and atmospheric circulation anomalies Russ. Meteorol. Hydrol. 42 (8) 518–28
[70] Sitnov S A and Mokhov I I 2018 Anomalies in the atmospheric methane content over Northern Eurasia in the summer of 2016 Doklady Earth Sci. 480 (1) 637-41
[71] Kizyakov A I, Sonyushkin A V, Leibman M O, Zimin M V and Khomutov A V 2015 Geomorphological conditions of the gas-emission crater and its dynamics in Central Yamal Earth’s Cryosphere XIX (2) 15–25 (in Russian)
[72] Arzhanov M M, Mokhov I I and Denisov S N 2016 Impact of regional climatic change on the stability of relic gas hydrates Doklady Earth Sci. 468 (2) 616–18
[73] Arzhanov M M and Mokhov I I 2017 Stability of continental relic methane hydrates for the Holocene Climatic Optimum and for contemporary conditions Doklady Earth Sci 476 (2) 1163–67
[74] Marcott S A, Shakun J D, Clark P U and Mix A C 2013 A reconstruction of regional and global temperature for the past 11300 years Science 339 1198-1201