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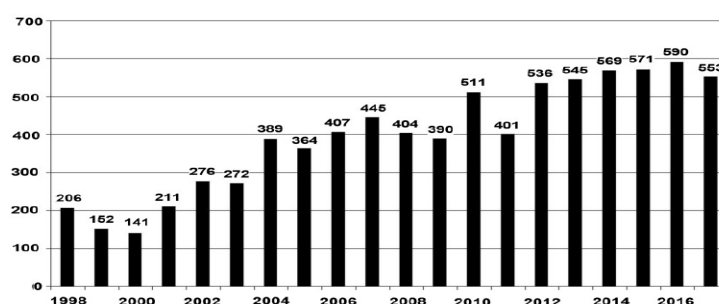
Figure 1. Changes in the number of dangerous meteorological phenomena in Russia since the end of the 20th century.

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 CO_2 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 CO_2 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 of the mesopause temperature - about a century long or more [10], according to results of simulations with the global climate model for the 20-21 centuries with consideration of anthropogenic influences.

The analysis of observations for surface air temperatures from the mid-19th century, conducted in [6], indicates the determining role of CO_2 content in the long-term (on a centennial time scale) changes in global and Arctic climate. The contribution of CO_2 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 ΔT 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 γ in the troposphere normalized to the corresponding average values for the Northern Hemisphere (NH), of the $d\gamma/dT$ parameter that characterizes sensitivity of γ to the change in the surface air temperature T and of the parameter $p=\gamma^{-1}(d\gamma/dT)\delta T$, 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 δT from reanalysis data for the period 1979-2014 [33]. The parameter $d\gamma/dT$ was estimated from the annual data using linear regression γ 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 γ with the surface temperature T indicates corresponding positive climate feedback.
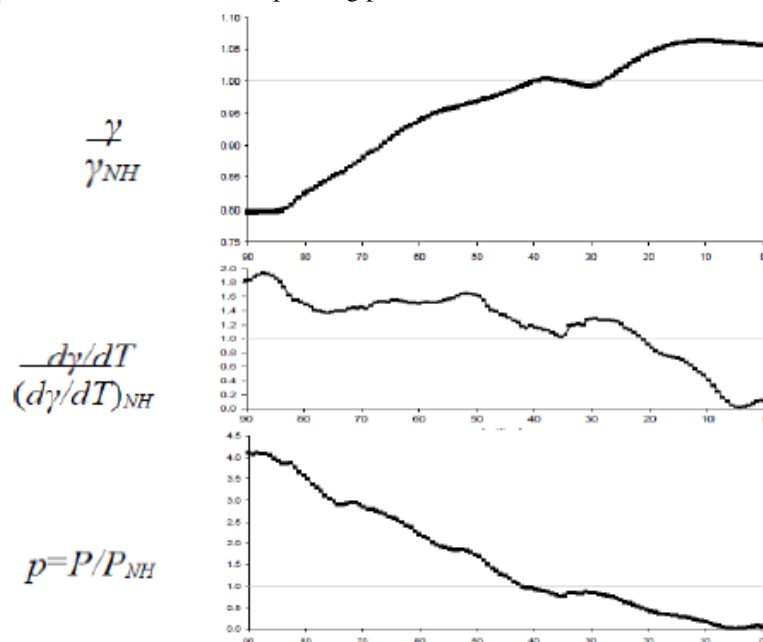

Figure 2. Latitudinal dependence of the estimates of the vertical temperature gradient in the troposphere, normalized to the corresponding average values for the Northern Hemisphere (NH), the parameter $d\gamma/dT$, which characterizes the sensitivity γ to changes in the surface temperature T, and the parameter $p=\gamma^{-1}(d\gamma/dT)\delta T$, which characterizes the relative role of variations in the vertical temperature stratification in the troposphere at different latitudes in the interannual variability δT, from reanalysis data for the period 1979-2014.

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 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-latitudinal troposphere the moisture is not so efficiently transported in the atmosprere 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.
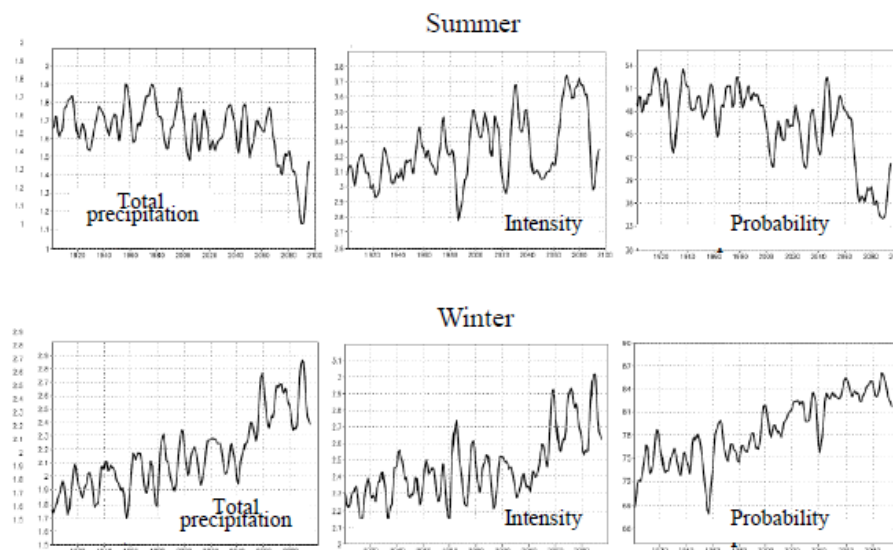
Figure 3. Model estimates of seasonal changes in precipitation characteristics in the Moscow region (50–60°N, 30–45°E) for possible climatic changes until the end of the 21st century: total precipitation (mm / day), intensity (mm / day), probability (the number of days with precipitation).

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

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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_k

$$\frac{dU}{dT}U^{-1} = -2\frac{dm}{dT}m^{-1},$$

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 intensity, 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-latitudinal 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 methanhydrates 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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