Global and regional climate anomalies and trends: Assessment of contribution of natural and anthropogenic factors from observations and model simulations

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Abstract. Trends in current global and regional climate change are estimated based on observations and reanalysis data, as well as on the basis of model simulations. Special attention is paid to climate changes in the Arctic and North Eurasian regions. Temperature and sea ice changes in the Arctic and Antarctic are compared. The processes contributing to the enhancement of regional climate variability are considered. The role of natural and anthropogenic factors in climate change and the ability of models to adequately simulate current climate changes are assessed. Possible changes in relative contribution of natural and anthropogenic CO$_2$ and CH$_4$ emissions in the North Eurasian regions under global warming are discussed.

1. Introduction

Current regional and global-scale climate conditions are characterized by significant trends and variability [1-3] (Fig. 1). The strongest trends and anomalies of the surface temperature are manifested in the Arctic latitudes - the so-called Arctic Amplification (AA) [4]. The estimates for contribution of various climatic feedbacks to the Arctic (Polar) amplification are presented in [5,6]. Simplest (analytical) estimates of the comparative role of different factors in the AA formation with a negative relationship between the meridional temperature gradient and the temperature changes can be obtained using the energy balance model consideration [7,8]. The AA manifestation depends on the connection of the surface albedo (snow, ice), meridional heat transfer, atmospheric water vapor content, lapse rate and other climate variables with temperature.

The brightest manifestation of current climate changes associated with the AA is the rapid reduction of the Arctic sea ice extent [1,2]. The NSIDC data (http://nsids.org) based on satellite measurements from 1979 display trend of decrease of the Arctic sea ice extent in September larger than 1% per year. The observed changes admit the possibility that, already in a few decades, there will be no sea ice in the Arctic basin in summer–fall months. Against the background of a rapid decrease in the Arctic sea ice extent related with strong Arctic warming, variations in the sea ice extent in the subantarctic and Antarctic ocean areas with relatively weak temperature changes are associated with a significant influence of natural variability and climatic quasi-cyclic processes like El Niño, Antarctic Oscillation, Interdecadal Pacific Oscillation [9-17].
Figure 1. Zonal-mean anomalies (left) and trends (on right) of the surface temperature for recent 30-years (from above) and 50-years (from below) periods by GISS data (data.giss.nasa.gov/gistemp/).

2. Results

Table 1 presents estimates of the sensitivity $dS/dT$ [%/K] of the Arctic and Antarctic sea ice extent $S$ from satellite data since 1979 (http://nsidc.org) to changes in surface temperature $T$ in the Northern Hemisphere and in the Southern Hemisphere, respectively, from reanalysis data for different months [17]. Statistically significant (at the level of two standard deviations) are highlighted. According to Table 1 the sensitivity estimates in the Northern Hemisphere are statistically significant for all months. In the Southern Hemisphere the most significant sensitivity estimates were obtained in the autumn months. Moreover, a negative correlation was obtained for all months, with the exception of August, September and October, with insignificant positive correlation. A more detailed estimates with the use of cross-wavelet analysis shows the increase in the coherence of long-period variations in the extent of the Arctic and Antarctic sea ice with hemispheric anomalies of surface temperature since the early 2000s. The coherence of the extent of Antarctic sea ice with surface temperature in the Antarctic has been significantly manifested over the past two decades for variations with periods characteristic for El Niño phenomena. The results of the cross-wavelet analysis reveal a significant coherence of variations in the last decades of the extent of the Antarctic sea ice with natural quasicyclic processes, including the El Niño phenomena, the Antarctic oscillation (Antarctic circumpolar mode). Significant coherence of interannual and decadal variations of the Antarctic sea ice extent was manifested in recent years with the Antarctic Oscillation [17].
Table 1. Estimates of the sensitivity of the Arctic and Antarctic sea ice extent [%/K] from satellite data (http://nsidc.org) for different months to corresponding changes in surface temperature for the Northern Hemisphere and the Southern Hemisphere from the ERA5 reanalysis data for the period 1979-2019. Estimates significant (at the level of two standard deviations, in brackets) are highlighted.

| dS/dT [%/K] 1979-2019 | Northern Hemisphere | Southern Hemisphere |
|------------------------|---------------------|---------------------|
| months                 |                     |                     |
| January                | -8,2(±1,1)          | -13,0(±12,0)        |
| February               | -6,5(±1,0)          | -5,9(±10,8)         |
| March                  | -6,7(±0,8)          | -26,2(±11,0)        |
| April                  | -7,1(±1,0)          | -25,0(±8,0)         |
| May                    | -10,1(±1,2)         | -11,8(±4,2)         |
| June                   | -15,2(±1,0)         | -7,6(±4,0)          |
| July                   | -26,8(±2,5)         | -4,5(±2,0)          |
| August                 | -38,2(±3,6)         | 0,1(±1,9)           |
| September              | -40,9(±4,3)         | 3,6(±2,3)           |
| October                | -27,7(±2,3)         | 2,1(±1,8)           |
| November               | -12,7(±1,3)         | -4,4(±2,4)          |
| December               | -9,1(±1,3)          | -12,6(±6,2)         |

The results obtained indicate significant coherence with changes of temperature in the interannual variability not only of the sea extent in the Arctic, but also in the Antarctic. Against the background of a rapid decrease in the extent of Arctic sea ice due to strong Arctic warming, the interannual and ten-year variations in the extent of sea ice in subantarctic and Antarctic waters (with a general weak temperature trend) are associated with a significant influence of natural climatic modes like El Niño-type modes, Antarctic Oscillations (Antarctic Circumpolar Mode), an inter-decade Pacific Oscillation. In this regard, in recent decades, according to satellite data, against the background of global warming, a tendency has been observed for an increase in the Antarctic sea ice extent, although not statistically significant.

Similarly to [18], it is possible to estimate the ratios of the amplitudes $\Delta T$ and $\Delta S$ and periods ($T_o$) of cyclic variations of $T$ and $S$ and long-term (centennial) trends of temperature increase ($dT/dt$), and sea ice extent decrease ($dS/dt$), the periods with opposite sign changes ($dT/dt<0, dS/dt>0$) are possible. In the simplest case of harmonic variations for temperature $T(t)$ and $S(t)$ the corresponding condition for possibility of $dT/dt<0$ and $dS/dt>0$ under long-term warming (with $(dT/dt) > 0$ and $(dS/dt) < 0$) is as follows:

$$\Delta S \geq (T_o/2\pi) (-dS/dt) (dT/dt)$$.
At the same time, there is a tendency toward an increase in the coherence of long-period variations in the extent of the Antarctic sea ice with the temperature regime in the Antarctic and for the Southern Hemisphere as a whole. The dramatic changes in the Antarctic sea ice extension in recent years are consistent with the revealed long-term trends from observations and projected model estimates. The global-scale climate changes are manifested in the frequency and intensity of extreme regional events. The number of dangerous meteorological phenomena in high- and mid-latitudinal Russian regions since the end of the 20th century has increased on average by about 6-7% per year (Fig. 2). In 2018, this number was more than 4 times greater than in 2000 (http://www.meteorf.ru/).

Figure 2. Number of dangerous meteorological phenomena in Russia by Roshydromet data.

The highest frequency of extreme events (especially related to hydrological processes) is noted in the warm months of the year [18]. This is due in accordance with the Clapeyron-Clausius ratio with an increase in the moisture capacity of the atmosphere under warming, which increases the probability of extreme precipitation. Changes in atmospheric circulation, in particular, a weakening of the meridional temperature gradient and geostrophic velocity of the zonal wind at mid-latitudes, with general tropospheric warming, contribute to an increase in spatial heterogeneity of climate variables, including precipitation, within the same latitudinal zone. The formation of temperature anomalies is associated with a change in the intensity of atmospheric jets. An increase in their waviness contributes to an increase in the role of meridional processes relative to zonal ones. At the same time, the probability of meridional flows of cold air from polar latitudes and warm air from lower latitudes increases. The peculiarities of intra-seasonal and intra-monthly variability are manifested, in particular, in cold air outbreaks in spring and summer related with the atmospheric jet-stream variations associated with the global warming [19-24]. Analysis of atmospheric conditions associated with “Russian Heat Wave” (initiated by blocking situation over European part of Russia) in the summer of 2010 revealed the prognostic significance of the upstream jet variations at the 200 hPa level [25].

The most significant contribution to the interannual variability of the global surface air temperature is associated with the El Nino/Southern Oscillation (ENSO) effects. The corresponding teleconnections are noted even with the Arctic regions. The noted connections of weather and climate anomalies in the North Eurasia regions with the El Nino processes are associated with a significant influence of El Nino / Southern Oscillation (ENSO) on the North Atlantic Oscillation which controls westerly winds and storm tracks across the North Atlantic [26]. In particular, significant relationships with ENSO were noted for hydrological conditions in the Caspian Sea basin [27]. In [27], the ability of climate models was demonstrated not only to reproduce the strongest variations in the Volga River runoff and the level of the Caspian Sea in the 20th century, but also to adequately assess possible
changes in the 21st century. In particular, according to results of model simulations, taking into account anthropogenic forcings, a noticeable decrease in the Volga runoff and the Caspian Sea level for next decades in the first third of the 21st century was expected. A marked drop in the level of the Caspian Sea is currently observed after reaching its maximum level at the very end of the 20th century (in 1995).

Different types of El Nino are manifested with the associated various regional anomalies of weather and climate conditions [28]. According to [29,30] the possibility of various ENSO regimes can be shown with the use of the simplest model like DAO (Delayed Action Oscillator) model [31,32]. In [33], peculiarities and changes of various possible phase transitions for different El Nino types and periods during 1891-2015 were estimated. In particular, different El Nino types were characterized by the sea surface temperature (SST) in the Nino3 (150–90W, 4N–4S), Nino3.4 (170–120°W, 4N–4S) and Nino4 (160E–150W, 4N–4S) regions in the equatorial latitudes of the Pacific Ocean (JMA index, ftp://www.coaps.fsu.edu/). El Nino (E, warm) and La Nina (L, cold) phases were defined by the index values of at least 0.5K and at most –0.5K, respectively, during several consecutive months. All the other cases were characterized as neutral phases (N). Nine possible phases of transitions for ENSO were analyzed, including $E \rightarrow N$ as a transition from the El Nino phase in the beginning of the year (winter in the Northern Hemisphere) to the neutral phase at the beginning of the next year, $E \rightarrow L$ as a transition from El Nino to La Nina phase, and $E \rightarrow E$ as a prolongation of the El Nino phase [28,33]. There are significant differences in phase transitions for different El-Nino types with significant changes for different time intervals.

**Figure 3.** Mean spatial distribution of the surface air temperature anomalies in May-July in Northern Eurasian regions for the $E \rightarrow L$ transitions (in 1988, 1998, 2007 and 2010).

Figure 3 presents an example for the spatial distribution of the average anomalies of surface air temperature in May–August in Northern Eurasia estimated in [28,33] for the transition $E \rightarrow L$ (1988, 1998, 2007, and 2010). The abnormally high surface air temperature is registered for European part of Russia for the transition $E \rightarrow L$ for spring-summer months that is typical of atmospheric blocking conditions. The wave structure typical of quasi-stationary planetary (Rossby) waves is manifested at these conditions. In this structure the zones of positive and negative anomalies of temperature alternate depending on longitude. Such structure (with the wave number equal to 4) was clearly pronounced in the summer of 2010.

Similar, for estimation of ENSO dynamics and its effects, the Oceanic Nino Index (ONI) can be used (https://www.cpc.ncep.noaa.gov/). It is characterized by the sea surface temperature (SST) anomalies in the in the Nino 3.4 region (5N-5S, 120-170W). Warm (El-Nino, E), cold (La-Nina, L) or neutral (N) phases are defined with the use of a threshold of ± 0.5 °C for the 3 month running means of
SST anomalies for a minimum of 5 consecutive overlapping seasons. Figure 4 shows ENSO phase transitions with the use of ONI for the period 1990-2019. For 2019, which began in the El Niño phase, by August there was a transition to the neutral phase with its extension until the end of the year (E→L transition). For such phase transitions, an increased probability of a drought regime in some Asian regions was estimated [28]. As in 2019, with a similar previous phase transition in 2003, there was also an abnormal heat in Western Europe and very high fire activity in Eastern Siberia, in particular north of Lake Baikal. It is worth noting that the winter of 2003-2004 in Russia it was very warm. On this basis, an increased probability of a very warm winter 2019-2020 in Russia could be expected in advance.

![Figure 4. ENSO phase transitions with the use of ONI for the period 1990-2019.](image)

To what extent the noted climatic anomalies and trends are associated with natural and anthropogenic factors can be estimated using Wiener-Granger causality similarly to [34]. The contributions of radiative forcing of greenhouse gases (GHG) and natural climate variations to the trends in global surface air temperature (GSAT) and surface air temperature for different latitude belts depend on time intervals. Quantitative estimates can be obtained, in particular, from observational data similar to [34] with the use the Wiener–Granger causality. Table 2 shows such estimates for the relative contribution of the GHG radiative forcing to the temperature trends for periods of various duration in the past decades relative 2012. During the recent decades, GHG contribute stronger to the trends of GSAT and tropical surface air temperature, while their contribution to the trends in surface air temperature in the middle and high latitudes is smaller. At relatively short time scales about 2-3 decades, contribution of natural climate variations is comparable in magnitude with that of greenhouse gases and could even exceed it, while at scales of about half a century or larger the GHG contribution to the temperature trends is dominating.

Climate sensitivity to different natural and anthropogenic forcings depends on positive and negative climate feedbacks. It is necessary to take into account that natural ecosystems can decelerate or accelerate global warming in dependence on regional climate conditions. In the Russian regions the CO₂ uptake by terrestrial ecosystems currently decelerate global warming, while their CH₄ release into the atmosphere accelerate it. The general effect of natural fluxes of these greenhouse gases from the
Russian regions for current climate conditions contributes to the deceleration, but this can be changed significantly with further warming [3,35].

**Table 2.** Estimates for the relative contribution of the GHG radiative forcing to the temperature trends for periods of various duration in the past decades relative 2012.

| Period (years) | Global mean | Tropics | Middle Latitudes | High Latitudes |
|----------------|-------------|---------|------------------|---------------|
| 20             | 0.58        | 0.61    | 0.41             | 0.33          |
| 30             | 0.62        | 0.71    | 0.44             | 0.41          |
| 50             | 0.82        | 0.86    | 0.68             | 0.64          |
| 130            | 0.93        | 0.98    | 0.99             | 0.98          |

**Table 3.** Relative (%) cumulative temperature potential of anthropogenic (A) and natural (E) emissions of CO$_2$ and CH$_4$ from the territory of Russia under different scenarios of anthropogenic forcing. The absolute cumulative temperature potential of anthropogenic emissions for $T_H = 2030$ under scenario RCP 8.5 is taken as 100%.

| Scenarios   | RCP 2.6 | RCP 4.5 | RCP 6.0 | RCP 8.5 |
|-------------|---------|---------|---------|---------|
| $T_H=2030$  | 78      | -6      | 72      | 88      |
| $T_H=2050$  | 81      | -12     | 69      | 107     |
| $T_H=2075$  | 78      | -13     | 66      | 106     |
| $T_H=2100$  | 86      | -8      | 67      | 99      |

Table 3 presents estimates of relative (%) cumulative temperature potential of anthropogenic (A) and natural (E) emissions of CO$_2$ and CH$_4$ from the territory of Russia under different scenarios of anthropogenic forcing based on model simulations for different periods [35]. The absolute cumulative temperature potential of emissions was estimated for periods $[T_0, T_H]$ with $T_0 = 1990$ and different $T_H$. At the beginning of the 21st century, the terrestrial ecosystems of the Russian regions contribute to general stabilization, but from the middle of the 21st century the stabilization starts decreasing due to the growth of natural methane emissions and reduction in CO$_2$ absorption. According to Table 3 the contribution of natural emissions to stabilization accumulated since 1990 can be fully compensated by the end of the 21st century for the RCP 6.0 scenario. The contribution of natural emissions from the territory of the Russian regions to the warming for the RCP 8.5 scenario can be already positive to the end of the 21st century [35]. Special risks are related with forest fires with the increase of their probability under warming [36-37].

3. Conclusions

In recent years, a number of significant climate anomalies and trends with a new phenomenon and features of climate change have been noted. Significant climate changes are noted in the Arctic with a fast decrease in the sea ice extent. The formation of craters on Yamal (for the first time in 2014) and adjacent regions has been revealed. The formation of such craters under climate warming is associated with the decomposition of methane hydrates with gas emissions into the atmosphere in regions of permafrost [38-40]. It may be an indicator that modern warming has reached mid-Holocene level at least for some regions [18].

The abrupt decrease of the Antarctic sea ice extent in 2016 seems to be the first indicator of a new tendency expected from model simulations under global warming. General increase in the Antarctic sea ice extent during past decades was related with a general decrease of ocean temperature in the corresponding Antarctic latitudes for the period with available satellite data for the sea ice extent from
the late 1970s. The noted regional decrease in ocean surface temperature for the last 4 decades against the background of the general warming of the Southern Hemisphere can be explained by the significant influence of natural climatic quasi-cyclic processes such as El Niño, Antarctic Oscillation, and Interdecadal Pacific Oscillation. For longer periods, in particular for the last 6 decades, a general increase in ocean surface temperature in the Antarctic latitudes is already displayed. With the extension of a satellite data set for sea ice in the coming years, against the background of general warming, a general tendency towards a decrease in the Antarctic sea ice extent with the surface temperature in the Antarctic and for the Southern Hemisphere as a whole.

The results of long-term data analysis indicate the dominant role of anthropogenic factors at the time intervals of about half a century or more [34]. At time intervals of one to two (or three) decades, natural climatic variability is very significant. For better general agreement between model simulations and observations, it is required that the models adequately describe the natural climate variability [41]. It should be also noted that natural climate variability associated with phenomena like El Niño can increase under global warming [42].

Some new climate processes and effects can be especially important in terms of the Paris Agreement conditions to keep the increase in global surface temperature below 2°C above pre-industrial level. In particular, according to obtained estimates one can expect under some scenarios, that the climatic effect of increasing greenhouse gas emissions into the atmosphere by natural ecosystems may exceed the corresponding absorption capacity of Russian regions by the end of the 21st century. In this case the total contribution of natural emissions to the atmosphere from the territory of the Russian regions may become positive [35].

Acknowledgments
The analysis was carried out in the framework of the RFBR projects (17-29-05098, 18-05-60111) and the RAS program “Climate change: causes, risks, consequences, problems of adaptation and regulation”. The analysis of causal relationships was carried out as part of the RSF project 19-17-00240.

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