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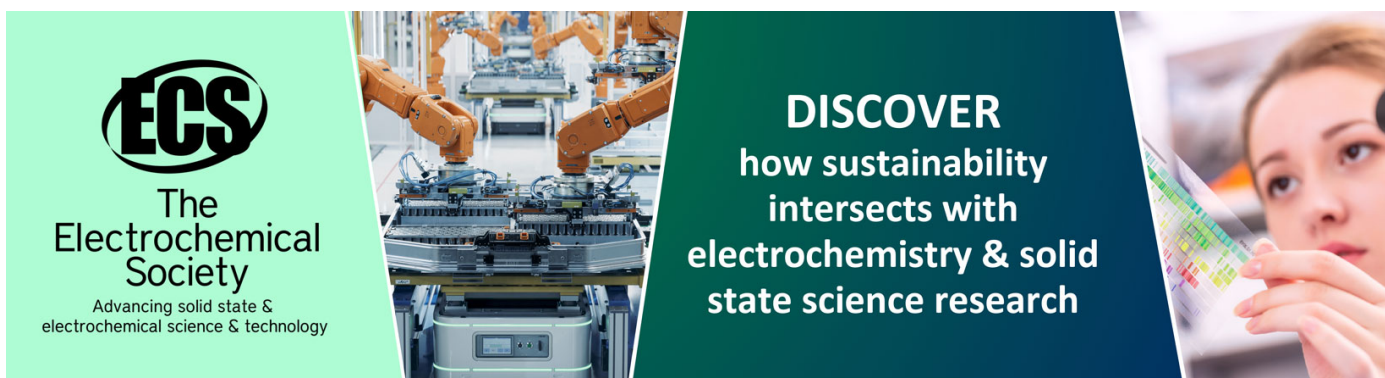
Weather and climate features of the Northern Hemisphere in 2019 in the context of long-period variability

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Weather and climate features of the Northern Hemisphere in 2019 in the context of long-period variability

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Abstract. The features of the spatial and temporal distribution of the main meteorological values in the Northern Hemisphere in 2019 are considered. A brief description of climate change on the background of long-period variability of extreme meteorological phenomena, which identified by WMO climate indices, is given. Quartile analysis and nonparametric Mann-Kendall criterion are used to assess the significance of changes in the frequency and intensity of extreme meteorological phenomena in different regions of Russia. The increase in the growth of the average temperature in the Northern Hemisphere in the spring and summer of 2019 compared to 2018 and early 2019 is noted. The prolonged large-scale anomalies of weather regimes were observed in the warm period of 2019: heatwaves in Western Europe, in the south of European Russia, in Siberia, Alaska, and as well heavy rainfall in the Irkutsk region and in the south of the Far East. Possible mechanisms of weather and climate changes in the Northern Hemisphere are discussed. The focus is on the Arctic, which is the most vulnerable to climate warming. It is concluded that, with an abundance of physical hypotheses, there are many contradictions and uncertainties in the study of the mechanisms of weather and climate variability. Solving the problems requires further research based on modern technologies, the development of satellite monitoring systems and hydrodynamic modeling.

1. Introduction

In recent decades, economic losses associated with climate variability and extreme weather events impact, have increased dramatically. Significant climate trends are observed in almost all meteorological parameters in all seasons and regions of the planet.

Climate change is closely related to weather change. The concepts of weather and climate belong to the same subject field and differ mainly only in scale. The weather changes cover fluctuations with periods from a few hours to some days; climate works out over a long period - decades, centuries and so on. Models of climate and numerical weather forecasts are based on the same system of numerical representations of complete equations of hydro- and thermodynamics. The differences are because of the weather changes are determined mainly by initial conditions. In climate models priority is given to boundary conditions, associated with the state of the ocean, the cryosphere, and the chemical composition of the atmosphere.

Currently, thanks to the rapid development of computing and information technologies, there are real opportunities for the implementation of a unified system of weather and climate modeling, or a "seamless" approach [1]. Weather and climate are seen as a continuous process, combining movements of various scales from a few hours to several weeks, months, years, decades and more. The time range from sub-seasonal to seasonal, which corresponds to forecasts with a lead time of more than two weeks but less than a season, occupies the interval between weather and climate forecasts and is a central component for seamless forecasting [2].

Since the climate is understood as the "statistical regime" of atmospheric conditions (weather conditions), and climate norm as the "long-term average values" of weather characteristics [3], extreme meteorological phenomena (EMP) make a significant contribution into climate change.



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Weather and climate, covering a full range of different time scales, represent a single system with a variety of feedbacks arising from the nonlinear interaction of processes occurring in the atmosphere, ocean, cryosphere, biosphere and active layer of land. Therefore, in the process of changing climate other conditions, such as a reduction of the Arctic sea ice, increasing ocean temperatures, changes in radiation conditions, etc., are forming for the implementation of new weather extremes.

The purpose of this article is to study the features of spatial and temporal variability of the main meteorological values in the Northern Hemisphere in 2019 in the context of climate change. Particular attention is paid to the EMPs that have a significant impact on global warming.

2. Initial data and analysis methods

As the initial information for the solution of the problem were used:

- data of 236 stations located on the territory of the Commonwealth of Independent States (CIS) on temperature and precipitation from the archives of RIHMI-WDC (<http://meteo.ru/data>) and MAKT bases of the Hydrometeorological Center of Russia;
- surface data and data on levels AT-500 hPa, AT-850 hPa of NCEP/NCAR Reanalysis 2 archive of four-line reanalysis fields on $2.5 \times 2.5^\circ$ grid for 1981-2019;
- reanalysis of the ECMWF (ERA-Interim) global fields of average daily air temperature on the grid $2.5 \times 2.5^\circ$ for the period from 1981 to 2019;

The WMO Expert Team on climate change detection, monitoring and indices (ETCCDI) recommended climate indices to identify EMP (<http://etccdi.pacificclimate.org/>). These climate indices are widely used in the assessment of various aspects of climate change (see table 1).

Table 1. Climate Extreme Indices

Label	Index name	Index Definition	Units
SU25	Summer days	Number of summer days: Annual count of days when daily maximum temperature $TX > 25^\circ\text{C}$	Days
TXx	Max TX	The maximum daily maximum temperature each month	$^\circ\text{C}$
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when $TX > 90^{\text{th}}$ percentile.	Days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when daily minimum temperature $TN < 10^{\text{th}}$ percentile	Days
GSL	Growing season length	Let TG_{ij} be daily mean temperature on day i in year j . Count the number of days between the first occurrence of at least 6 consecutive days with $TG_{ij} > 5^\circ\text{C}$. And the first occurrence after 1 st July of at least 6 consecutive days with $TG_{ij} < 5^\circ\text{C}$.	Days
R10mm	Heavy precipitation days	The annual count of days when the daily precipitation amount on day $> 10\text{ mm}$	Days
R20mm	Very heavy precipitation days	The annual count of days when the daily precipitation amount on day $> 20\text{ mm}$	Days
CDD	Consecutive dry days	Count the largest number of consecutive days where the daily precipitation amount $< 1\text{ mm}$	Days
CWD	Consecutive wet days	Count the largest number of consecutive days where the daily precipitation amount $\geq 1\text{ mm}$	Days

The quartile analysis [4] is one of the possible nonparametric ways to filter outliers and extremes. The results of the statistical analysis were presented both in tabular form and in the form of graphs made separately for two periods: 1961-1989 (29 cases) and 1990-2018 (29 cases) for these indices for

236 stations, situated on the CIS territories.

The Mann-Kendall test (statistics U) was used to estimate the statistical significance of the trend in the time series (1961-2018) of indices [5]. Let the null hypothesis H_0 be that the sample is chronologically ordered, independent, and uniquely distributed. Statistics U follows a standard normal distribution with zero mean and unit variance. The critical value of U at P -value = 0.05 (5 % significance level) is 1.96. If the empirical value of the criterion is $U \geq 1.96$ or $U \leq -1.96$, then the null hypothesis is rejected and the trend is considered statistically significant.

Additional information was provided by:

- reviews of the state and trends of climate change, weather-climatic and main features of atmospheric circulation and weather in the Northern Hemisphere, obtained from the websites of the Hydrometeorological Center of Russia (<https://meteoinfo.ru>), North Eurasian Climate Center (NEACC) (<http://seakc.meteoinfo.ru>), Institute of Global Climate and Ecology (IGCE) (<http://climatechange.igce.ru>);
- Climate Diagnostic Bulletin of the U.S. Climate Prediction Center (https://www.cpc.ncep.noaa.gov/products/CDB/CDB_Archive_pdf/pdf_CDB_archive.shtml);
- reviews of the National Snow and Ice Data Center, supported by NOAA and NASA (http://nsidc.org/data/seaice_index).

3. Brief description of climate changes

Over the territory of Russia, located in different climatic zones, the range of climate changes and extreme meteorological phenomena is especially large. According to IGCE, in most of the CIS countries in 1976-2018, the warming trends have been continuing. The most significant changes in average annual air temperatures are observed in Northern Siberia, North-Eastern Yakutia and Northern Chukotka (up to $1.1^\circ\text{C} / 10$ years). In summer, the main changes, associated with climate warming, occur in the south-western part (0.80 - $0.97^\circ\text{C} / 10$ years): in Moldova, Ukraine and adjacent regions of Russia. At the same time, in the east of Kazakhstan and the south of Western Siberia, the air temperature values are close to the average ($0.1^\circ\text{C} / 10$ years - $0.2^\circ\text{C} / 10$ years). In the summer period in the north-east of Kazakhstan, there is a small area of weak cooling (up to $-0.1^\circ\text{C} / 10$ years).

These trends reflect long-term changes in climate indices characterizing the temperature regime. According to the results of quartile analysis, the most significant increase in the duration (WSDI index) and intensity (SU25 and txp90 indices) of heat waves is observed at the stations of the south-west of European Russia (figure 1(a), 1(b), 1(c), Kursk and Rylysk) and in the Arctic (figure 1(d) and 1(e), Khatanga). At the same time, there is a significant increase not only in the average duration (median distribution), and variability (intra-quartile range) of heat waves, but also in the boundaries of the upper extremum, as well as outliers in 1990-2018 compared to 1961-1989. The transformation of the distributions is particularly noticeable at their ends. In the Arctic regions of Siberia and the Far East, climate warming is supported not only by an increase in the duration of heat waves, but also by a decrease in the duration of cold waves (CSII index) (figure 1(f)). In Eastern Kazakhstan and Southern-Western Siberia, changes in the main climate indices between 1961 and 2018 are statistically insignificant ($U < 1.96$). The results of the analysis, performed for the two periods, differ little and confirm these conclusions (figure 1(g), 1(h) and 1(i), Karaganda and Zaisan).

The distribution of local coefficients of the linear trend of precipitation anomalies for 1976-2018 is more complicated. The most significant trends in precipitation are typical for the Caspian regions of Kazakhstan, Uzbekistan to the North of the Aral Sea, Yakutia, and the coast of the Sea of Okhotsk (more than 5 % of the norm per 10 years). In summer, most of the European territory is dominated by a tendency to decrease of precipitation, in the Asian, on the contrary, their increase.

The links between climate trends and changes in precipitation indices are not always clear. In the Southern (figure 2(a), Rylysk) and North-Eastern European Russia (figure 2(d), Amderma) the positive trends in the maximum continuous duration of dry periods (CDD index) are statistically significant. Negative trends in the changes of CWD indices (figure 2b and 2e), r10mm and r20mm (figure 2(c) and 2(f)), characterizing the duration and intensity of precipitation, are present, but require the use of more

representative samples to confirm the significance. In Yakutia and on the Okhotsk coast of the Magadan region, changes in the CDD index (figure 2(g)) confirmed the trends (figure 2(f) and 2(i)) of the precipitation increasing (CWD and r20 indices).

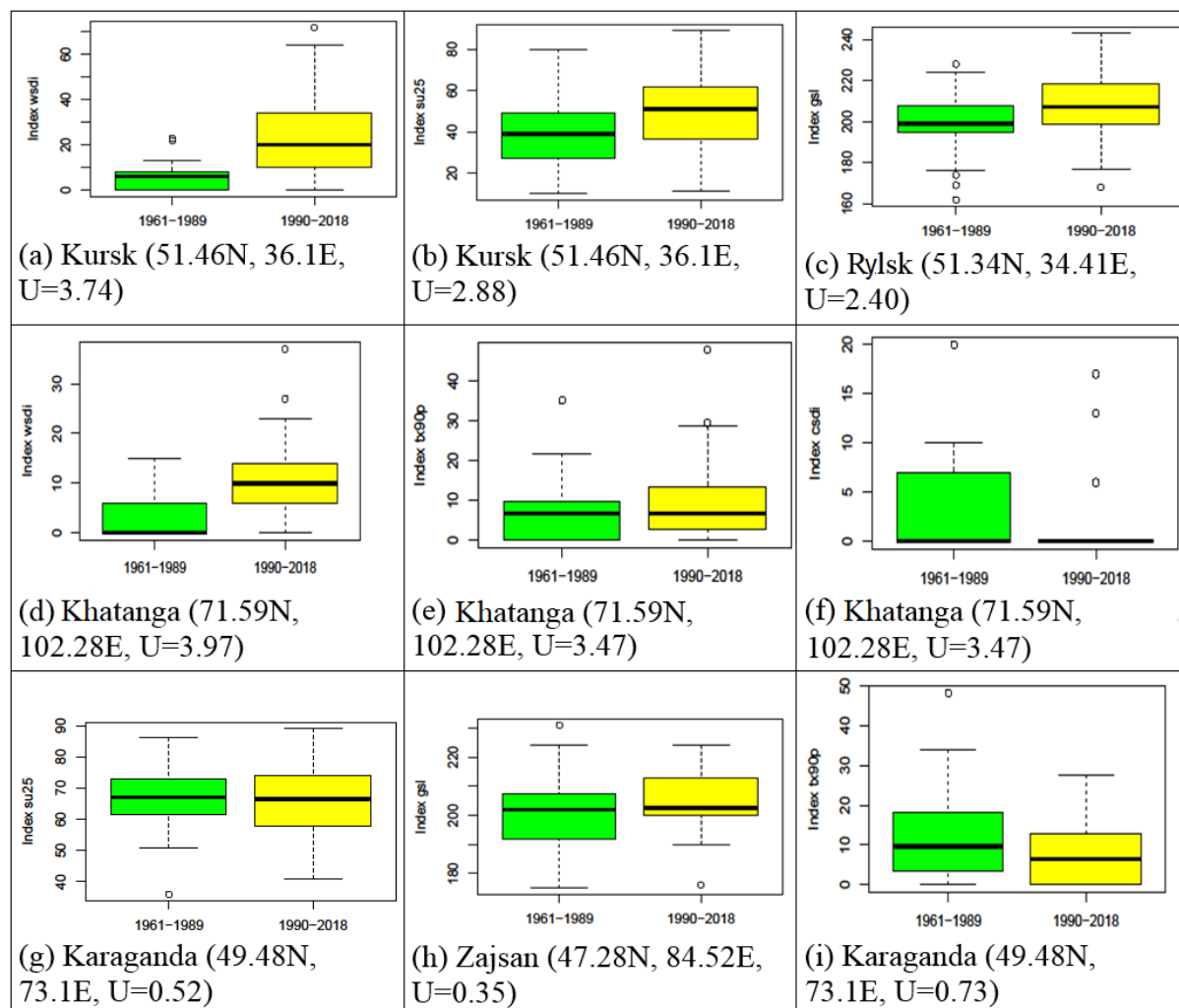


Figure 1. Comparison of boxplots of climatic indices characterized the temperature conditions at stations are performed for two periods: 1961-1989 and 1990-2018 (29 cases). A trend was considered statistically significant (at $P\text{-value} \leq 0.5$) when the Mann-Kendall (MK) statistics U was either ≥ 1.96 or ≤ -1.96 .

Commentary: The lower and upper boundaries of the boxes correspond to the values of the 25th percentile ($q_{0.25}$ -lower quartile) and 75th percentile ($q_{0.75}$ -upper quartile). The Interquartile Range: $IQR = q_{0.75} - q_{0.25}$. The dividing lines between less and more unusual points are known as the fences. Upper outer fence: $UOF = q_{0.75} + 3IQR$, Lower outer fence = $q_{0.25} - 3IQR$; Upper inner fence: $UIF = q_{0.75} + 3IQR/2$, Lower inner fence: $LIF = q_{0.25} - 3IQR/2$.

A significant temperature increase in combination with an increase in the frequency and intensity of EMP in Southern European Russia and in the Arctic determines the increased vulnerability of these regions to climate change.

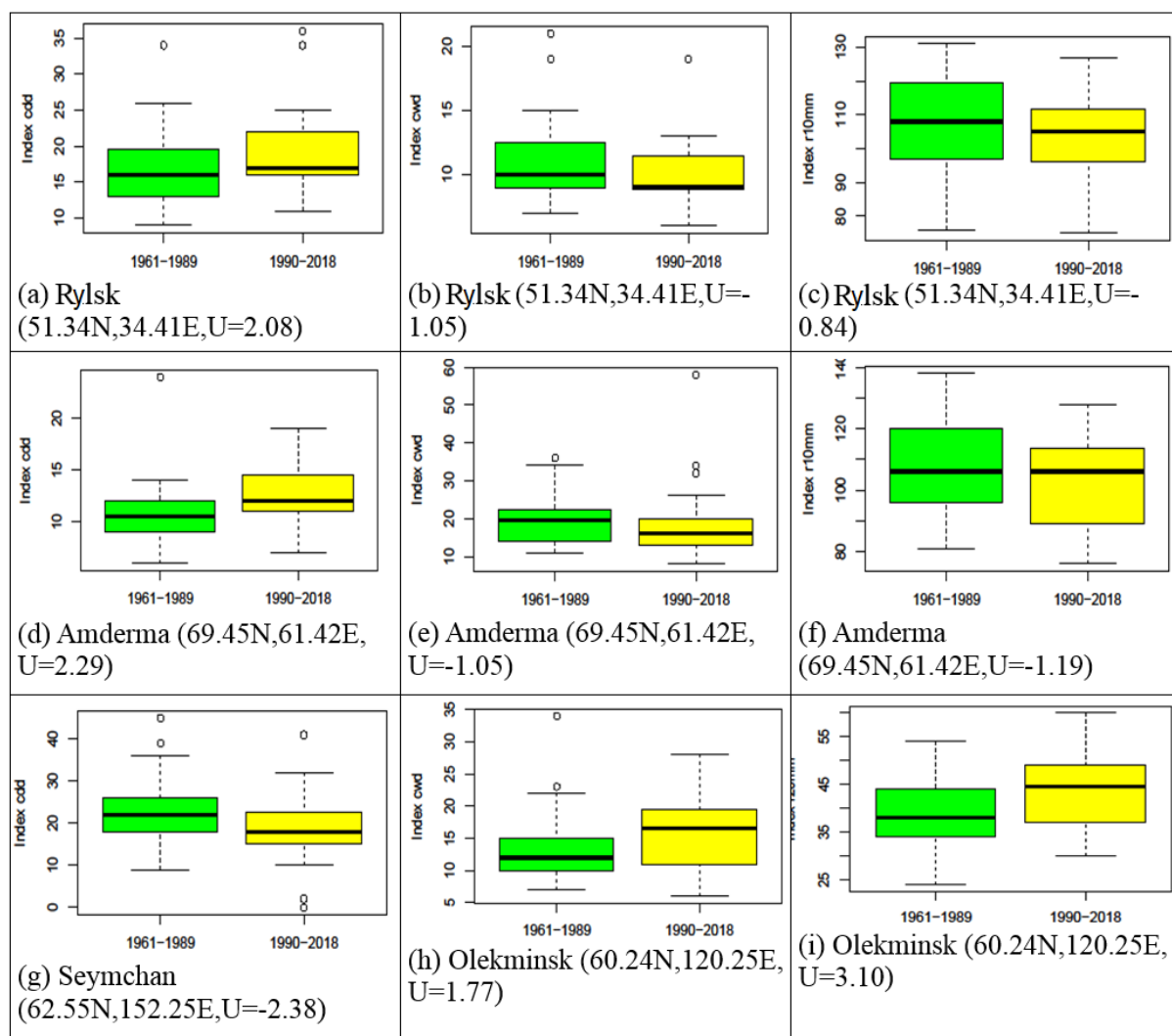


Figure 2. Comparison of boxplots of climatic indices characterized the precipitations at stations are performed for two periods: 1961-1989 and 1990-2018 (29 cases). A trend was considered statistically significant (at $P\text{-value} \leq 0.5$) when the Mann-Kendall (MK) statistics U was either ≥ 1.96 or ≤ -1.96 .

4. Temperature and precipitation

After a slight decline in 2018, including the winter of 2018 -2019, the mean air temperature began to rise again. According to preliminary estimates, 2019 in the Northern Hemisphere is expected to be the second or third warmest year on record, 2016 remains the warmest year. The most significant deviation from the climate in summer was observed in Alaska and adjacent seas, in North-Eastern Canada and nearby Islands (to 3-4 ° C), in the center of Western Europe (2-3 ° C), in the North of Eastern Siberia and the Far East (4-5 ° C) in the North and North-East Africa (up to 2-3°). June 2019 was the hottest month on record (since 1891) in Alaska, Europe, North Africa and the Arctic. In Alaska, March and July 2019 were also extremely warm. Temperatures in the Arctic, since March, remained in the top five highest. In Russia, June was the warmest month in the south of the European part, as well as in the north of Siberia and the Far East.

Temperature anomalies have led to significant changes in the Arctic sea ice extent. It was the smallest on record since 1979 in April, June, July and October, the second smallest (following 2012) in May and August, and the third smallest in September. The sea ice around Alaska, which usually rests

until June, this year, disappeared in March. In Greenland in late July-early August, the process of unprecedented rapid ice melting was detected on 90 % of the surface of the glacier. The most significant reductions of the sea ice were observed in the Beaufort Sea, the East Siberian and Chukchi seas, where at the end of October it remained significantly below average.

The distribution of precipitation is more complicated and characterized by high spatial and temporal variability. Large amounts of precipitation in 2019 fell in Eastern and southern China, as well as in India. Heavy rains at the beginning of the warm period took place in parts of the United States, where May became the second wettest month in the history of meteorological observations. In Russia, in the north-west of the European part, in the Irkutsk region and in the south of the Far East in parts, precipitation exceeded the norm by 1.5-3.0 times.

5. Extreme weather events

Large-scale anomalies of weather regimes, developing at sub-seasonal time intervals are of particular importance in the context of long-term climate change. Such processes in summer are associated with heat and drought, catastrophic floods, etc. They have a relatively low frequency, but spread, as a rule, over large areas and cause great social and economic damage. The indices WSDI (heat waves) and CSDI (cold waves), which determine long-term large-scale anomalies of air temperature, could be one of the possible characteristics of this kind of phenomenon.

There are maps of the spatial distribution of these indices, modified for the average daily air temperature in the first (figure 3(a)) and the second half of summer 2019 (figure 3(b)). Presented heat waves are predominant in almost the entire territory of the Northern hemisphere, and there are practically no cold waves, except for the North-West of European Russia in the second half of summer.

In Western Europe, Alaska, Canada and Russia, the duration of heatwaves in some areas exceeded 25-30 days. June was the warmest month in Austria, Germany and Hungary. In late June, new temperature records were set in the South of France (up to 45.9 °C), in Spain (up to 44 °C), in Germany (up to 39.6°C). In July, absolute maximum temperatures were hit in France, Germany, Belgium, the Netherlands, the United Kingdom and Finland. Because of prolonged stable abnormally hot and dry weather, forest fires were observed over areas of Alaska, Canada, Siberia, including some parts inside the Arctic Circle.

In the Russian Federation the number of dangerous phenomena that caused significant damage, 2019 was not extremely big. In the period from January to October, 320 severe hydrometeorological events were registered. It is about 1.3 times less than in 2018 (424). But on the background of long-term large-scale anomalies of atmospheric circulation, heat waves took place in the south-west of the European territory, in Siberia and Chukotka. Prolonged heavy rainfall in the Irkutsk region and in the south of the Far East caused floods (figure 4).

In the Irkutsk region in the basins of the Iya, Uda, Biryusa and Oka rivers abundant precipitation of rare occurrence led to the flood that engulfed Western and Central parts. It was registered a sharp increase in water level for 365-913 cm. The event caused 24 death, 9 people were missing. The flood on the Amur River in 2019 was the second most intensive in the history of hydrological measurements following 2013. In the Primorsky region, where 5 ex-typhoons brought heavy rains, August 2019 was one of the rainiest on record. In Vladivostok, the monthly amount of precipitation distinguished 521 mm, which is above the previous one of 418 mm belonged to 1943.

At the same time, in Yakutia, in the prolonged abnormally hot and dry weather conditions, it was necessary to introduce a state of emergency because of the shallowing of the Lena River. There was even a threat of water shortage at some city water intakes. Hot and dry weather contributed to the high fire danger in some areas of the Irkutsky and Krasnoyarsky regions, as well in the Republic of Sakha (Yakutia). According to "Avialesokhrana" (Federal Forestry Agency), by the beginning of September, the area of wildfires in Siberia raised up to 3.7 million hectares, in the far East 4.3 million hectares. In general, in Russia in the last two years, there has been an increase in the area of forest traversed by fire: in 2018, by the beginning of September, it amounted to 7.0 million hectares, in 2019 - 8.2 million

hectares.

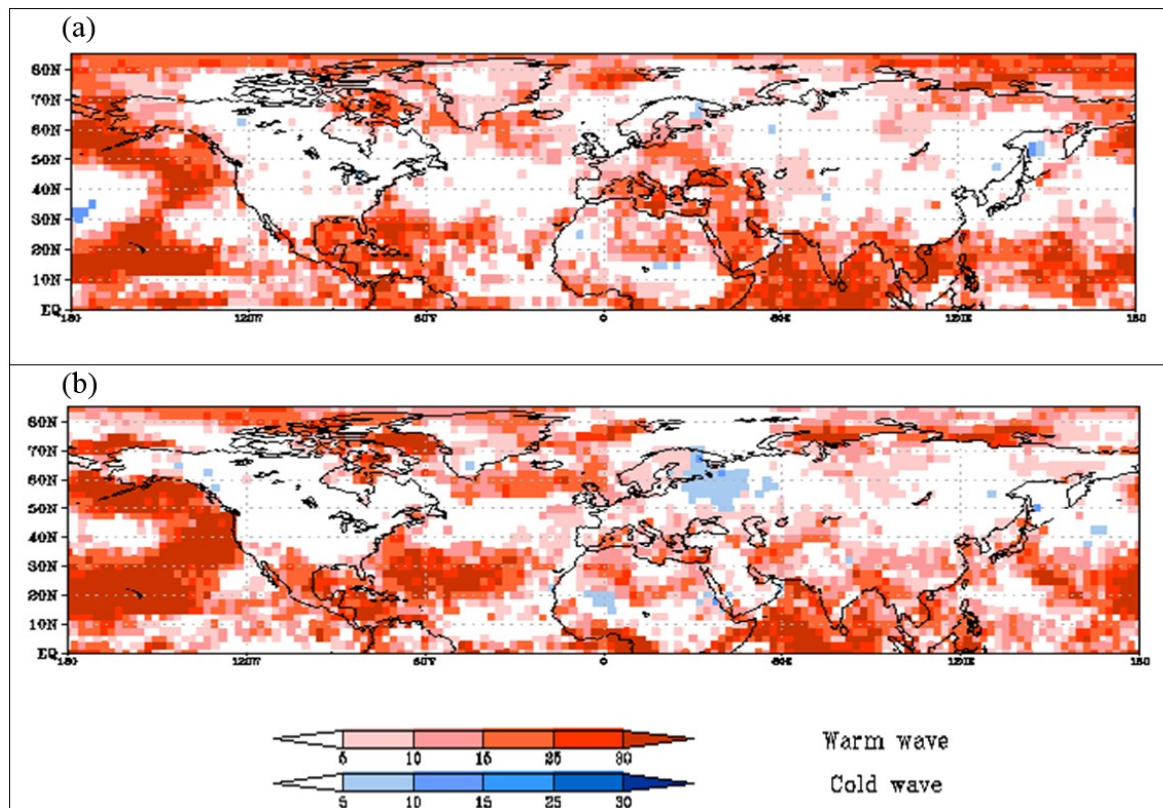


Figure 3. Duration (days) of cold ($P < 10\%$) and warm ($P > 90\%$) waves. Era Interim for 46 days started on 2019.06.01 (a) and on 2019.07.14 (b).

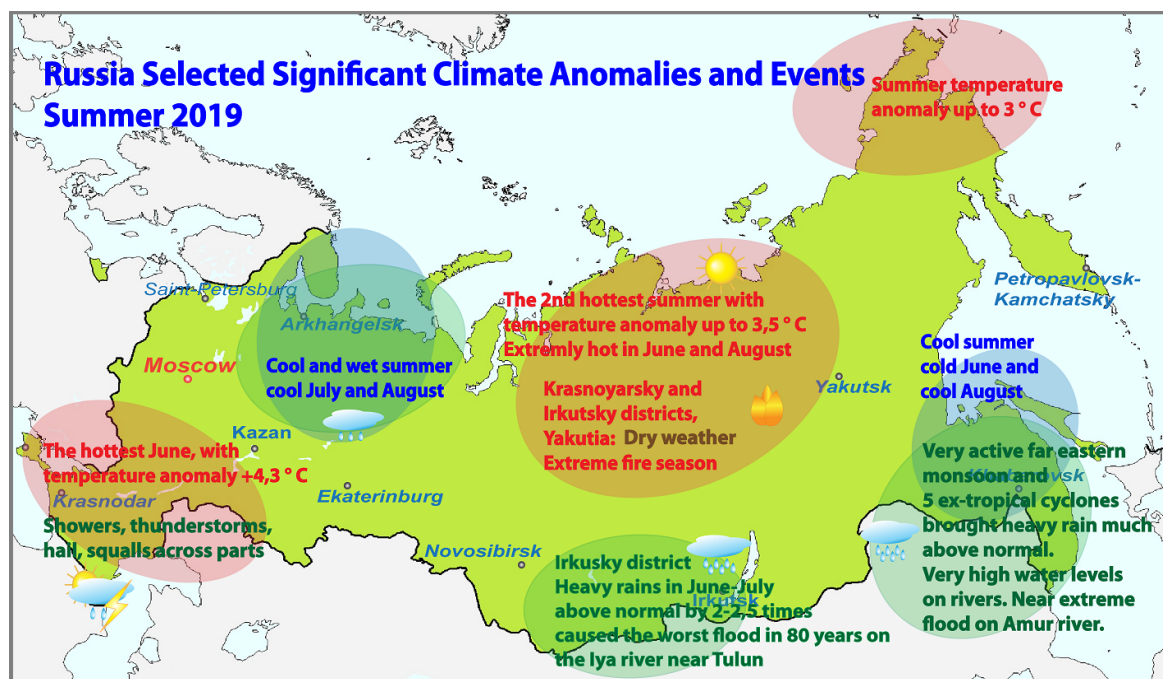


Figure 4. The selected significant climate anomalies and events, Summer-2019 in Russia.

6. Atmospheric circulation

Not only the new extreme values of meteorological parameters and their variability accompanied global warming. In addition, long-term changes of atmospheric circulation associated with the location and intensity of centers of action of the atmosphere, the frequency and intensity of cyclones, shifting storm-tracks, etc. take place. The warm period 2019 was highlighted by the quick gain of the Arctic anticyclone in the stratosphere in May, and the latest since 1958 reconstruction of the circulation in winter mode ended on 21 September. During the entire warm period (May till September), the predominance of positive geopotential anomalies in the troposphere near the pole was noted. The near-polar cyclonic vortex was significantly weakened and shifted to the South relative to its climatic position. The unusual circulation in the region of the pole was reflected in the position of the planetary high-altitude frontal zone, which in some months differed significantly from the climatic one. In May, June and August its deviations from the normal to the North in parts reached almost 20° of latitude. At the same time, deviations to the South in all months did not exceed an average of $5-10^\circ$.

Perturbations of the circulation in the region of the pole affected atmospheric processes occurring at middle latitudes. In general, it could be noted the increase in the degree of the longitudinal atmospheric circulation over the Northern Hemisphere. According to the climate prediction center (CPC, <https://www.cpc.ncep.noaa.gov/products>), atmospheric circulation regimes associated with the negative phase of the North Atlantic oscillation index, (NAO, from May to October) and the positive phase of the East Atlantic oscillation index (EA, from June to October) dominated for a long period over the North Atlantic and Europe. They both are characterized by increased intensity of longitudinal air exchange. In other regions of the Northern hemisphere, circulation regimes were not as stable.

7. Ocean surface temperature

During the warm period of 2019, positive sea surface temperature (SST) anomalies prevailed in most of the North Pacific against the background of the warm (positive since March 2019) phase of the Pacific decadal oscillation (PDO). The average surface temperature of the Pacific in the Northern Hemisphere in the summer of 2019 was an absolute positive extreme. In the tropical zone of the Pacific, there has been a transition from a weak El Nino to neutral conditions. In the Indian Ocean, the spatial distribution of SST anomalies corresponded to the positive phase of the dipole with positive (negative) anomalies in the West (East) affecting the intensity of the monsoon circulation over Southeastern Asia. Significant SST anomalies associated with the negative phase of the tripole were observed in the North Atlantic. The signal from the ocean favored to the realization of the negative phase of NAO.

8. Possible mechanisms of weather and climate variability

The question of the links between weather and climate changes is still open and requires a detailed and in-depth analysis. Processes in the North polar region play a special role. According to the intergovernmental panel on climate change (IPCC) [6], the Arctic is one of the four most vulnerable regions to climate change (as well as small islands States, Africa and the deltas of big rivers in Africa and Asia). Climate warming in the Arctic is much faster and larger than in other regions. A number of studies [7,8] emphasize the global importance of climate change in the Arctic from one side and the lack of knowledge of physical processes and feedbacks acting in the climate system from another.

The most important role in climate warming in the Arctic is assigned to atmospheric circulation. A number of authors [9,10] resort to the use of balance relations for moisture and energy. According to their estimates, heat transition by poleward atmospheric currents is the main input part of the energy balance of the atmosphere at high latitudes.

In some studies, the peculiarities of changes in temperature regime and precipitation in the Arctic are considered within the framework of the concept of global and regional atmospheric circulation regimes associated with Arctic (AO) and North Atlantic (NAO) oscillations [11,12]. It is assumed that the temperature and precipitation fields are formed under the influence of circulation regimes, which

arise because of nonlinear interaction between the synoptic and planetary scales [13].

In recent years, much attention has been paid to the study of feedbacks between the temperature regime in the Arctic and the atmospheric processes in the middle latitudes [14,15]. On the background of the warming of the Arctic over the past two decades, there is an increase in the frequency of cold winters in Russia and North America. A number of studies [16,17,18] have attempted to explain large-scale anomalies of major meteorological variables in the context of climate change. One of the most common hypotheses [17] relates changes in atmospheric circulation and the occurrence of anomalous weather regimes in Eurasia and North America with a decline in the sea ice extent and the amplification of warming in the Arctic (AWA), against which the polar-equator temperature gradient in the troposphere decreases. As a result, the oscillations of planetary waves and their amplitudes increase, the movement of waves in the zonal flow slows down. This contributes to the formation of blocking regimes and the occurrence of extreme weather.

In [16], using a model of the global circulation of the atmosphere with given boundary conditions on the ocean surface (ice concentration and thickness, SST) from several climate models of CMIP5, the reaction of the atmosphere to the impact of AWA during the onset of summer ice-free conditions was studied. The simulation results showed that at AWA, the oscillations of planetary waves are not amplified, since the polar-equator temperature gradient in the middle and upper troposphere changes very slightly.

Thus, despite the abundance of physical hypotheses, questions remain open about the mechanisms of interaction between weather regimes and climate change.

9. Conclusion

According to preliminary estimates, 2019 will join 2016 and 2017 in the top three warmest years in the Northern Hemisphere. In the warm period of 2019 the most significant positive temperature deviations were observed in Alaska, in the North-West of Canada and the nearby Islands, in Western Europe, in the north of Eastern Siberia and the Far East, in Northern Africa. In Russia, June was the warmest on record in the southern districts of the European part and in the north of the Far East.

Large amounts of precipitation in 2019 fell in Eastern and Southern China and India. Many parts of the United States experienced heavy rain at the beginning of the warm period, and May became the second wettest month in the history of meteorological observations. In Russia in the North-West, as well as in the Irkutsk region and in the south of the Far East in parts monthly amounts of precipitation exceeded the norm by 1.5-3.0 times. At the same time, dry station extremes (below the 5th percentile) were observed in the south of the European territory and in Siberia.

The number of dangerous weather events in 2019 was not extreme. However, on the background of long-term large-scale anomalies of weather regimes, floods on rivers in the Irkutsk region and on the rivers of the Amur River's basin were noted. Hot and dry weather contributed to the high wildfire risk in parts of the Irkutsk and Krasnoyarsk regions, as well in Yakutia.

A significant peculiarity of the warm period (May-September) was the predominance in almost all of the troposphere, positive anomalies of geopotential heights near the pole, as well as an increase of the intensity of longitudinal circulation over the Northern Hemisphere.

In the fields of anomalies of ocean surface temperature in the warm period of 2019, significant excess above the average was observed. So the SST in the Northern half of the Pacific has become an absolute positive extremum.

Positive temperature anomalies were the cause of near record values of the Arctic sea ice extent.

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