Analyzing extreme weather phenomena in northern regions in the context of modern climate change

V P Kuznetsova
Nizhnevartovsk State University (NVSU), Russia, Nizhnevartovsk

E-mail: ver597@yandex.ru

Abstract. At present, various world regions face statistically significant weather anomalies indicating transformations in the climate system. Climate change processes are manifested both at the global and regional levels under local physical and geographical conditions. Northern regions, where climate change is clearly observed, experience extreme weather phenomena able to affect the quality of land resources, livelihoods of the population, and the local economy. Depending on their distribution, manifestation, frequency and quantitative parameters, these phenomena are often characterized by a destructive potential which entails a need to monitor the unfavorable natural processes in order to take them into account when planning the territory. This paper analyses some dangerous hydrometeorological phenomena associated with climate changes observed in the Khanty-Mansiysk Autonomous Area Yugra.

1. Introduction
Accompanied by extreme weather phenomena and hazardous natural processes in various regions of the globe, modern climate change generates much interest within the scientific community. Extreme weather and climate monitoring has become particularly important for scholars studying the specifics of environmental changes. Recently, an increase in the frequency of extreme weather events caused by climate change has been observed almost everywhere. Climatic anomalies and extreme events are increasingly observed in different regions of Russia [1]. The frequency of occurrence of dangerous hydrometeorological phenomena increases, and an estimate is given for individual constituent territories of the Russian Federation [2]. Scientists establish the impact of climate change on the frequency of extreme hydrometeorological events [3]. There is a need to improve methods for studying weather hazards, creating databases of extreme events [4]. In northern latitudes, studies of natural risks caused by hazardous meteorological phenomena are of particular relevance, which must be taken into account for sustainable development of the social, economic sphere [5, 6, 7]. It was found that at the beginning of the XXI century the climate extremality in Western Siberia has been increasing, it began to appear more often in one or another area of the region, depending on the season. This predetermines the transition of extreme climate events into the category of dangerous meteorological phenomena [8]. Studies confirm a significant increase in the long-term indicators of average annual air temperature, which leads to intensive permafrost thawing and affects the environment of northern regions. Scholars observe current climate warming in the northern latitudes, leading to a noticeable shift in natural zone boundaries [9].

Studying unfavorable and dangerous hydrometeorological phenomena is highly essential, considering their extreme character and threat to the environment, economy, human life, and public health, and a possibility of environmental and economic damage [9, 10].
According to Roshydromet, about a thousand dangerous hydrometeorological events, including agrometeorological and hydrological phenomena, are annually observed in Russia. The largest number of dangerous hydrometeorological phenomena over a 12-year period was recorded in 2008 (1090 phenomena) and 2018 (1040 phenomena).

Heavy precipitation (snow, rain, heavy rain), severe wind (including squall), hail, snowstorms and abnormally cold weather in winter, as well as extreme fires lead to the greatest damage of the environment, complicating the economic activity of the regions, bringing damage to the economic sectors and public activities [10, 11].

In Russia, dangerous meteorological events prevail in spring and summer (with the greatest number in July, decreasing in August, June, May), with the number of events increasing each year since 1998 [11].

In this regard, the issue of climate change and its impact on natural processes and increased number of extreme weather events is highly relevant, especially considering the situation in northern regions.

2. Models and Methods
The Khanty-Mansiysk Autonomous Area Yugra (hereinafter KhMAO Yugra) is characterized by uncomfortable and extreme living conditions, with a moderate, harsh continental climate. The territory is equated to the Far North. The climate is diverse, with rapid changes of weather during all seasons, especially during the transition from autumn to winter and from spring to summer, daily and seasonal air temperature fluctuations, long and cold winters, and short cold summers [12].

This paper analyzes extreme weather conditions and hazardous hydrometeorological phenomena, and studies the response of the natural environment to modern climate change based on phenological phenomena in KhMAO Yugra. To identify the response of the natural environment to climate change, we collected, processed and associated analysis of long-term series of climatic and phenological information on the studied territory. We have analyzed long-term series of meteorological parameters based on the data of specialized arrays for climatic studies made by the Russian Scientific Research Institute of Hydrometeorological Information. According to the data provided by the Aviation Meteorological Station of Nizhnevartovsk, we calculated the values of individual monthly and average annual climatic indicators and analyzed the indicators of minimum and maximum air temperatures. A significant amount of data on the timing of phenological phenomena in Nizhnevartovsk and its suburbs for 2007–2020 has been accumulated, and certain meteorological data series for the respective years have been analyzed. An analysis of the timing for the onset of phenological phenomena led to some conclusions about the time boundaries and trends in the occurrence of phenological seasons under the conditions of climate change observed in the taiga zone of KhMAO Yugra.

Using methods of information analysis, mathematical and statistical processing of data, an analysis of arrays of meteorological and phenological information was carried out. The statistical method of research was used to process and analyze meteorological and phenological data by grouping, calculating average and relative values, graphical reception, data comparison, and compiling parallel series. Trends of meteorological and phenological data series were analyzed. The objects of phenological monitoring are specific species of plants and animals, as well as elements of non-living nature that undergo cyclical changes during the year. The statistical method of research was used to process and analyze meteorological and phenological data by grouping, calculating mean and relative values, graphical reception, and data comparison. To determine the spatial and temporal variability of the regional climatic conditions, we have analyzed long-term average annual air temperature, the precipitation amount, and the snow cover height at the meteorological stations in Berezovo, Oktyabrskoye, Khanty-Mansiysk, Ugut, and Nizhnevartovsk. In addition, we have analyzed the long-term duration of snow cover in Nizhnevartovsk region.

3. Results and discussion
Modern warming in the northern regions, with its rates rapidly increasing and extending the global average rates [11], which is clearly
observed in KhMAO Yugra. Long-term data series on air temperature provided by the meteorological stations indicate a tendency for an increase in the average annual air temperature in the taiga zone of KhMAO Yugra over the past 32 years (Figure 1).

![Figure 1](image-url) Long-term variations of the average annual air temperature (°C) in KhMAO Yugra for 1988-2019 (according to data provided by meteorological stations in Berezovo, Oktyabrskoye, Khanty-Mansiysk, Ugut, and Nizhnevartovsk) [13].

The analysis of the minimum and maximum air temperature indicators in the autumn-winter seasons in Nizhnevartovsk in 2007-2020 reveals extreme indicators of the temperature regime, which allows identifying some specific features of climate warming in this northern region (Table 1, Figure 2).

Table 1. Minimum and maximum air temperature indicators (°C) in Nizhnevartovsk. autumn-winter seasons of 2007-2020 [14].

| Air temperature (°C) | September | October | November | December | January | February |
|-----------------------|-----------|---------|----------|----------|---------|----------|
| **2007-2008**         |           |         |          |          |         |          |
| Min (Date)            | -1.5 (23.9) | -4.3 (16.10) | -20.2 (23.11) | -39.9 (21.12) | -36.7 (3.1) | -29.4 (12.2) |
| Max (Date)            | +20.1 (5.9) | +12.4 (5.10) | +5.7 (4.11) | -2.2 (3.12) | -3.1 (5.1) | +1.8 (25.2) |
| **2008-2009**         |           |         |          |          |         |          |
| Min (Date)            | +0.4 (30.9) | -16 (19.10) | -28 (30.11) | -32.8 (17.12) | -40.5 (29.1) | -40.8 (9.2) |
| Max (Date)            | +27.5 (1.9) | +14.9 (9.10) | +4.6 (2.11) | -0.6 (5.12) | -3 (1.1) | -6.5 (28.2) |
| **2009-2010**         |           |         |          |          |         |          |
| Min (Date)            | +0.2 (17.9) | -18.5 (26.10) | -36 (27.11) | -43.8 (28.12) | -43.2 (2.1) | -41.1 (25.2) |
| Max (Date)            | +22.8 (9.9) | +18.8 (1.10) | +1.4 (1.11) | +0.2 (3.12) | -13.2 (28.1) | -11.1 (16.2) |
| **2010-2011**         |           |         |          |          |         |          |
| Min (Date)            | -2.6 (15.9) | -2.4 (20.10) | -31.8 (30.11) | -35.3 (21.12) | -35.6 (1.1) | -34.7 (14.2) |
| Max (Date)            | +21.8 (21.9) | +11.7 (13.10) | +5.1 (6.11) | -8.4 (14.12) | -7 (14.1) | -4.4 (11.2) |
| **2011-2012**         |           |         |          |          |         |          |
| Min (Date)            | +0.9 (12.9) | -18.8 (31.10) | -29 (25.11) | -29.8 (16.12) | -34.6 (17.1) | -31.6 (1.2) |
characterized by persistent frosts, abnormally cold temperatures, with a deviation of -13...-19°C from the ten-day norm, in the second part of November. December was also cold with a deviation of -3...-7°C from the norm [13]. The winter season of 2009-2010, with prolonged frosts from December to February, as well as the periods of January-February 2013-2014 and 2018-2019, with unfavorable frosty conditions, were characterized by rather low temperatures below -40°C (Table 1, Figure 2).

![Figure 2. Minimum and maximum air temperatures (°C) in Nizhnevartovsk in the autumn-winter periods of 2007-2020 [14].](image)

Based on the data provided by the Federal Service for Hydrometeorology and Environmental
Monitoring, the winter of 2019-2020 was very warm in the whole Northern Hemisphere. The air temperature anomaly (+2.254°C) had reached its maximum value since 1886, and generally that winter was really warm everywhere in Russia, with an anomaly of +5°C [15].

As for KhMAO Yugra, the winter season of 2019-2020 had been extremely warm over the entire observation period, with the minimum air temperature reaching only -34.5°C (on December 25), according to the data provided by the meteorological station in Nizhnevartovsk. February 2020 was abnormally warm, with the air temperatures not falling below -26.6°C (on February 9), which was commensurate with the average air temperature in February in some past years. A new temperature record was registered on February 13, 2020, with the air temperature rising to an anomalous value of +12.1°C. The average air temperature in February 2020 was only -9.3°C, which is usually close to the average monthly temperature in March. During this period, the changes in weather conditions entailed such phenomena as early thaws, intense snow melting, which were unusual for the area and led to significant changes in the natural rhythms.

Following the winter season, the spring-summer period of 2020 in KhMAO Yugra also distinguished itself by an unusual meteorological situation and temperature records. As in 2017 and 2019, March 2020 became very warm (the average monthly temperatures were -3.4°C, -2.8°C, and -3.5°C, respectively). April 2020 was extremely warm (with the maximum average temperatures since 2007, reaching +5.8°C). May 2020 was particularly warm, with average temperatures of +13.8°C, which is comparable with the average temperatures of the summer months in the northern latitudes (Figure 3). According to the Federal Service for Hydrometeorology and Environmental Monitoring, the air temperature anomaly in Western Siberia in the spring of 2020 was +6.69°C [16].

![Figure 3. Average air temperatures (°C) for the spring-summer months of 2007-2020 in Nizhnevartovsk [14].](image)

In the long-term, we have observed an increase in the average annual air temperature. For instance, the data of the Nizhnevartovsk Meteorological Station showed that in 2007-2019 the average air temperature was -1°C and there is a tendency for increase in the average air temperature. In 2007, 2008, 2011, 2015, 2016, and 2019, the observations showed quite high indicators of the average annual air temperatures in the studied region. In Russia, 2019 was the fourth warmest year observed since 1936, with the average annual temperature 2.07°C higher than the average norm typical for 1961-1990 [11]. According to HydroMetCenter of the Russian Federation, 2015 and 2019 were among the warmest years in the history of meteorological observations. The coldest years were recorded in 2009 and 2010.

The study found that the average annual air temperature in Nizhnevartovsk has been -1°C for the last 10 years (2010-2019). As for 1988-2019, the year 2010 is characterized by the lowest air temperature (-3.6°C), which is 0.3°C lower than the values in 1998 and 2001. When analyzing the indicators of the average annual air temperature dynamics in Nizhnevartovsk over the past three decades, we discovered that the last decade was the warmest. As for 1990-1999 and 2000-2009, the
highest growth rates of the average annual air temperature were revealed.

In Nizhnevartovsk region, 2007 and 2015 were distinguished by the maximum amount of atmospheric precipitation (766 and 708 mm per year, respectively), which was particularly intense in certain seasons of the year along with an unusual thermal regime for this territory. Abnormal weather conditions characterized by a significant amount of atmospheric precipitation exceeding the climatic norm were established in May, June, and August 2007, and were also observed in the summer of 2015. The maximum amount of precipitation (149 mm) was recorded in Nizhnevartovsk region in August 2019 [13].

The timing of the snow cover formation and melting characterizing the duration of the frost period is the most important indicator of climatic changes in the northern latitudes. The number of days with snow cover in Nizhnevartovsk and its suburbs reaches 190-210 per year [17]. The taiga zone in the east of KhMAO Yugra (in Nizhnevartovsk) is characterized by a noticeable decrease in the duration of the period with a stable snow cover. After analyzing the duration of snow cover in Nizhnevartovsk, we discovered that the period of stable snow cover has a tendency to reduce in 1988-2020, with a confirmed statistical significance at the level of 0.05 (Figure 4).

Abnormally warm weather, with a maximum air temperature of +4.6°C in November 2008, +5.1°C in November 2010, and +2.8°C in November 2013, caused a very late formation of snow cover, which led to significant changes in the fauna biorhythms. As for snow melting, in the area under study it usually occurs in the first ten days of May or in April. In the spring of 2013, unfavorable weather conditions, with a rapid change of air temperature close to normal, but a relatively low average air temperature in May (+3.8°C), contributed to late snow melting in mid-May. In 2020, the snow cover melted by April 19, which was rather early due to abnormally warm weather, with the average air temperature reaching its maximum value since 2007 (+5.8°C) in April. In 1988-2020, the average stable snow period in Nizhnevartovsk amounted to 203 days.

The period of 2007-2019 was characterized by the maximum height of the snow cover for May (33 cm), which was observed in 2019.

During abnormally warm periods, meteorological conditions make a significant impact on the functioning of natural complexes and adjust the economic activities of the local population. For instance, in the winter of 2013-2014 the dates for commissioning winter roads and ice crossings were postponed to later dates due to the warm autumn and very late freeze-up on the rivers in KhMAO Yugra [17].

In 2019-2020, winter was extremely warm, which led to a limited operation of winter roads and ice crossings. In 2020, ice drift on the Ob River (in Nizhnevartovsk) started on April 17, which was a record early date because it was 12 days earlier than the average multi-year date for 2007-2020 (Figure 5).
In some years, extremely unfavorable hydrological conditions were observed in KhMAO Yugra, particularly, spring and summer floods leading to flooding of low-terrain areas. The previous large-scale floods in the region were caused by a large amount of snow in the winter period of 2014-2015, as well as by intense heavy rainfall in the summer of 2015, when the water level in the Ob River in Nizhnevartovsk reached 1061 cm [17]. High water levels cause serious damage to the ecological conditions, residential areas, transport and engineering infrastructure, and lead to revision of the established flood zone boundaries [18].

Such factors as temperature conditions, atmospheric precipitation distribution, time of snow cover formation and snow melting, and water levels in rivers and reservoirs have a significant impact on the development of fire hazards. In the area under study, natural fires are dangerous phenomena aggravated in extremely dry weather conditions. In 2012 the authorities introduced a special fire safety regime in the area, while 2020 was also distinguished by a high level of fire hazard [18].

Very strong wind (with a speed of 25 m/s and stronger; observed all year round), strong blizzard (visibility of less than 500 m at a wind speed of 15 m/s lasting more than 12 hours; observed during the cold season and in spring, up to early June), severe frost (in the period from mid-December to mid-February, for 3 days or more, with the minimum air temperature remaining below -45°C) are frequent local phenomena [17, 19].

In addition, climate change is accompanied by dangerous hydrometeorological phenomena that are not typical for the physical and geographical conditions of KhMAO Yugra. For example, in recent years tornadoes have been observed in the vicinity of the cities of Nefteyugansk (in the summer of 2010), Khanty-Mansiysk (June 2012) and Surgut (July 2016). On February 28, 2017, a snow thunderstorm was observed in Nizhnevartovsk. It was a rare natural phenomenon that had never been previously recorded in Yugra [13].

Climate change processes and extreme weather conditions have a significant impact on changing the timing of phenological phenomena in the northern region. Within the city, there is a tendency when first touches of spring are moved to earlier dates. In 2007-2020, the end of the pre-growing season determined by snow melt tended to occur at early dates in Nizhnevartovsk. Many of the phenological phenomena have a distinct reaction (early onset) to the spring warming periods in 2009, 2011, 2012, 2017, and, especially, in 2020. After overcoming the initial phenological stages, cold weather may return and weather conditions may deteriorate. For example, in 2010 and 2014 birch leaves completely unfolded and bird cherry trees blossomed relatively late.

The timing of the autumn phenological season in the taiga zone of KhMAO Yugra is diverse. Depending on the meteorological conditions and the nature of weather change, autumn can end in different times in KhMAO Yugra. In 2010, when a cold snap was noted unfavorable meteorological conditions were observed throughout the area, leading to early onset of the autumn season. In some years, the duration of autumn is reduced due to early formation of permanent snow cover, which is a phenological indicator of winter. During the study period, one could clearly observe a time shift in the onset of phenological phenomena in autumn towards a delay on the territory of the taiga zone of KhMAO Yugra.

Over the multiyear period under study, in some years the formation of permanent snow cover in Nizhnevartovsk occurred much later than the multiyear average: at the beginning and in the second
half of November (2008, 2010, and 2013) [20]. In the autumn and winter seasons, the observed warming processes are also manifested in delayed formation of freeze-up on rivers and lakes, the occurrence of thaws, and winter rain.

In 2007-2019, the territory of Nizhnevartovsk and its suburbs is characterized by an increase in the duration of the spring period compared with the average long-term value: +2 days in 2010, +32 days in 2011, +3 days 2012, +20 days in 2013, +14 days in 2017, and +2 days in 2018. There is also a steady trend towards an increase in the summer season, exceeding the long-term average, especially in 2012 (+11 days), 2016 (+12 days), 2017 (+8 days), and 2019 (+13 days). The extremely warm winter of 2019-2020, anomalous meteorological conditions in 2020 on the territory of KhMAO Yugra led to a very early onset of the spring and summer phenological seasons for the entire observation period (Figure 6). Within the city, birch leaves unfolded 23 days earlier than usual (May 07), while bird cherry trees blossomed as early as May 12, 24 days earlier than the average long-term date (this is the phenological indicator of the beginning of pre-summer, the final stage of the spring vegetation sub-season); rose hips and raspberries began to bloom by May 20 (26–27 days earlier than the long-term average, respectively).

As for the autumn season, there has been a tendency for a decrease in the duration, as evidenced by the linear trends in the onset of indication phenomena (the appearance of yellow strands on birches, complete yellowing of birches, complete exposure of birches, first snow) in 2007-2019.

In 2007-2020, the average long-term duration of phenological winter (from the formation of a stable snow cover to the beginning of snow melt and appearance of first thawed patches) in the city of Nizhnevartovsk and its suburbs is 122 days. During the specified period, the winter seasons of 2007-2008, 2009-2010, and 2014-2015 turned out to be the longest (144, 141, and 145 days, respectively), and the winters of 2010-2011 (72 days), 2011-2012 (108 days), 2013-2014 (115 days), 2016-2017 (118 days), and 2019-2020 (112 days) had the shortest duration.

The observed climate changes led to an increase in the frequency of extreme and catastrophic natural phenomena in 2007-2020 on the territory of KhMAO Yugra. Many important climate characteristics, such as the length of the frost-free period, the timing of snow cover formation, the onset of the first and last frosts and the distribution of precipitation, the timing of the onset of phenological periods have become more variable. Local climate change is most intensely manifested in spring and autumn, the transitional seasons of the year.

The observed climate change, the occurrence of extreme weather conditions in the northern
latitudes lead to a reaction of the natural environment, which manifests itself in the seasonal rhythm of the landscapes of the taiga zone, affect the river regime, the development of a fire hazardous situation, and determine the functioning of the economic activity of the population.

The observed climate change and the occurrence of extreme weather conditions in the northern latitudes lead to such an environmental reaction manifesting itself in the seasonal rhythm of the taiga landscapes, affecting the river regime, causing fire hazards, and determining the functioning of local economic activity.

4. Conclusions
This study allows making some conclusions on the peculiarities of modern climatic conditions and weather phenomena in the northern regions.
Studying data over a long period (1988-2019), we have observed a tendency to an increase in the average annual air temperature in the Khanty-Mansiysk Autonomous Area Yugra. We have found that the previous decade (2010-2019) was the warmest in the studied period. The observed climate change is characterized by seasonal weather anomalies, an increase in the atmospheric precipitation in some seasons of the year. We have observed an increase in the average height of snow cover and a decrease in the duration of the stable snow cover period.

This study showed a clear environmental reaction to modern climate change, which was manifested in a change in the timing of phenological phenomena in the taiga zone of KhMAO Yugra. The most intense change in the local climate is manifested in spring and autumn, the transitional seasons of the year, which is confirmed by the reaction of the phenological processes. In taiga, we have observed a shift in the phenological boundaries in the autumn season towards later dates.

In the context of modern climate change, dangerous hydrometeorological phenomena such as floods, natural fires, strong winds, intense rainfall, and severe frosts are observed in the region. Such phenomena can cause significant damage to the local economy and life of the population. The physical and geographical conditions of the northern region under study are characterized by atypical meteorological phenomena.

As for the vulnerable northern regions, it is essential to continue studying the unfavorable and hazardous hydrometeorological phenomena posing a threat to the natural environment, economy, life and health of the population in order to prevent adverse environmental and economic consequences.

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