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Article

Transformation of natural ecosystems affected by climate change in the Khanty-Mansi Autonomous Okrug – Yugra, Russia

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Abstract. The article presents the analysis of both observed (1960–present) and modeled (present–2100) changes in climate parameters, and their observed and probable consequences for ecosystems, including transformation. In 1960–2021, the average annual air temperature in the Khanty-Mansi Autonomous Okrug Yugra (KhMAO) was increasing as 0.33–0.52 °C/10 years, the annual amount of precipitation, as 3–15 mm/10 years. The number of dangerous hydrometeorological phenomena associated with abnormally low temperatures has decreased, while those associated with abnormally high temperatures, intense precipitation and droughts, have increased. The intensity of 19 dangerous hydrometeorological phenomena in the area is sufficient to cause significant damage to natural systems, including irreversible changes. The floods, wildfires, and droughts are the most dangerous. Changes in the timing of phenological events and shifts in the species ranges, including the emergence of invasive species, have been recorded. The results of bioclimatic modeling confirm that in the second half of the XXI century, the current boundaries of biomes will not correspond to the climatic conditions on most of the studied territory. The natural conditions of the northern taiga will be replaced by those observed for the middle taiga; in the southern areas, preconditions for steppe formation may emerge. Such climate change is favorable for 112 rare species with northern border of ranges located in KhMAO, but they are unfavorable for 20 arctic species. The potential change of biomes in the region to become of the southern (warmer) type will be accompanied by an increase in biological diversity and productivity of ecosystems.

Keywords: natural systems, climate-driven dynamics, climate risks, changing biome boundaries

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Научная статья

Трансформация природных экосистем в условиях изменений климата на территории Ханты-Мансийского автономного округа – Югры

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Аннотация. Приводятся результаты исследований наблюдаемых (с 1960 г.) и прогнозируемых (до конца XXI в.) изменений климатических параметров, а также их подтвержденных и вероятных последствий для экосистем, включая трансформацию. В 1960–2021 гг. среднегодовая температура воздуха на территории ХМАО росла со скоростью 0.33–0.52 °C/10 лет, а годовая сумма атмосферных осадков в этот период повышалась со скоростью 3–15 мм/10 лет. Количество опасных гидрометеорологических явлений, связанных с аномально низкими температурами, уменьшилось, связанных с аномально высокими температурами, а также интенсивными осадками и засухами – увеличилось. Интенсивность 19 опасных гидрометеорологических явлений на территории округа достаточна для нанесения существенного ущерба природным системам, включая необратимые изменения. К наиболее опасным относятся: паводки, природные пожары и засухи. Зафиксированы изменения сроков фенологических событий, ареалов видов, в том числе появление видов-вселенцев. Результаты биоклиматического моделирования подтверждают: к середине – концу XXI в. современные границы биомов не будут соответствовать климатическим условиям на большей части территории. Природные условия северной тайги сменятся пригодными для средней, на юге могут создаваться предпосылки для развития степей. Такие изменения климата благоприятны для 112 редких видов, находящихся вблизи северной границы распространения, и неблагоприятны для 20 арктических. Потенциальная смена биомов в регионе на более южные будет сопровождаться увеличением биологического разнообразия и продуктивности экосистем.

Ключевые слова: природные системы, климатообусловленная динамика, климатические риски, изменение границ биомов

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Introduction

Natural systems currently exist in conditions of both rapidly occurring global processes and increasing direct anthropogenic load. Climate change is considered one of the main factors of ecosystem transformation (IPBES, 2018).

Anthropogenically induced changes in the global average annual air temperature are now occurring at an unprecedented rate of 0.18 °C/10 years, which is an order of magnitude higher than that during any other geological epoch (IPCC, 2021). In Russia, climate change is occurring even more actively. The rate of warming since mid-1970s currently exceeds the global average by more than 2.5 times, in the Arctic, by 3.5 times. The average increase in average annual temperatures across the country is 0.51 °C/10 years, but in the Northern Polar Region it reaches 0.88 °C/10 years or even more (Doklad..., 2023; Tretii otsenochnyi doklad..., 2022).

This rate of change in climate parameters exceeds the rate of evolutionary adaptation of natural systems (IPCC, 2022; Pörtner et al., 2021; Tishkov, 2016). There is a desynchronization of the response of different systematic groups. Spatial unevenness of these changes, their direct and indirect effects can both enhance and restrain (or mask) the processes of spontaneous adaptation to climate change, increasing the vulnerability of some species and creating favorable conditions for others (IPBES, 2016; IPCC, 2014a, 2014b, 2022; Tretii otsenochnyi doklad..., 2022).

In addition to changes in temperature and in the amount and pattern of precipitation, modern climate change is characterized by an increase in the number and intensity of hazardous hydrometeorological phenomena that cause significant damage. In late XX–early XXI century, 150–200 of them were recorded in Russia annually, but since 2004, there are already 300–450 events recorded each year (Doklad..., 2023). Some of them are assigned as emergency situations, leading to the destruction or degradation of vegetation on thousands of hectares, mass death of animals, or/and irreversible changes in the ecosystems (Tretii otsenochnyi doklad..., 2022).

Western Siberia in general and the Khanty-Mansi Autonomous Okrug in particular are no exception. The assessment of climate risks during the preparation of the regional plan for adaptation to climate change confirmed the occurrence of all 24 hazardous phenomena from the national list¹: landslides, mudflows, avalanches, abrasion and thermal abrasion, reworking of the banks of reservoirs and lakes, karst; suffusion, subsidence of loess rocks, flooding, sheet and gully erosion, channel deformations, gully thermal erosion, thermokarst, heaving, solifluction, aufeis formation, flood, hurricanes, tornadoes, strong winds, heat, drought, frost, hail, heavy precipitation, and fire hazard in forests².

The task of reducing anthropogenic pressure on vulnerable ecosystems was set in regard to the climate change in the "Sixth National Report of the Russian Federation to the Convention on the Conservation of Biological Diversity" (Shestoi natsional'nyi doklad..., 2020). At the same time, two categories of natural systems were identified, grouped by the nature of the negative impact:

1) ecosystems subject to smooth, directional climate change that will gradually transform to come into line with abiotic factors;

2) ecosystems subject to hazardous climate-related phenomena corresponding to each of the natural zones in each region of Russia.

In the first case, the changes are irreversible. In the second case, the restoration of ecosystems close to the original ones depends on the strength of the hazardous phenomenon and the properties of the natural systems that have been affected. In most regions of Russia, the impacts on ecosystems of both smooth changes in weather and climate conditions and hazardous hydrometeorological phenomena, which enhance or inhibit transformation processes through direct and feedback loops, are manifested simultaneously (Tretii otsenochnyi doklad..., 2022).

The study aims to identify the transformation of natural systems of the Khanty-Mansi Autonomous Okrug – Yugra (KhMAO) in response to current and predicted climate change and the consequences of this transformation. Several tasks are solved:

1) Summarizing current and projected climate change and characterizing hazardous hydrometeorological events that may have a significant impact on biodiversity and thus may lead to the transformation of natural systems.

2) Describing the biological diversity of the study area.

3) Assessing the consequences of climate change and the impact of hazardous hydrometeorological phenomena on the natural systems of the area.

Materials and methods

The impacts of climate change and climate risks in KhMAO has been described in detail in a number of recent studies² (Globalnoe izmenenie klimata..., 2021; Lipka et al., 2023). This paper presents particular findings that are important for understanding the response of natural systems to changes in the abiotic environment.

We use the concept of **climate risk** of the Intergovernmental Panel on Climate Change (IPCC, 2014a). It defines climate risk as a "...probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard." In this context, "...hazard is the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources; the term hazard usually refers to climate-related physical events or trends or their physical impacts. Exposure is the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. Vulnerability is the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC, 2014b).

The concept of **adaptation to climate change** is also used in the IPCC interpretation: "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to

¹ Order of the Ministry of Economic Development of Russia dated May 13, 2021 No. 267 "On Approval of Methodological Recommendations and Indicators on Adaptation to Climate Change".

² Regional Plan for Adaptation to Climate Change in the Khanty-Mansi Autonomous Okrug – Yugra. (introduced by the Decree of the Government of the Khanty-Mansi Autonomous Okrug – Yugra dated 08.12.2022 No. 659-p).

moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects" (IPCC, 2014a).

More recent reports have defined **evolutionary adaptation** as "the process whereby a species or population becomes better able to live in a changing environment through the selection of heritable traits. Biologists usually distinguish evolutionary adaptation from acclimatization, with the latter occurring within an organism's lifetime" (IPCC, 2022).

The data on meteorological characteristics for 1960–2021, both real-time and daily resolution, published on the website of the All-Russia Research Institute of Hydrometeorological Information – World Data Center (RIHMI–WDC) (Bulygina et al., 2022a, b) were analyzed for five monitoring sites: Khanty-Mansi, Berezovo, Leushi, Nizhnevartovsk, and Korliki. The data on hazardous and adverse events, which caused damage in Russia, were also used (Shamin et al., 2023).

Information on biological diversity was obtained by analyzing publications and open access databases. The concept of biomes and their boundaries correspond to those proposed by the specialists of Lomonosov Moscow State University (Biomy Rossii, 2018; Bioraznoobrazie biomov Rossii..., 2020).

Information about rare species in the area corresponds to the latest published versions of the Red Lists and approved lists³ (Krasnaya kniga..., 2001, 2008, 2013) and to the official data from the Yugra Nature Supervision Agency⁴.

Results and discussion

Climate, its extremes and prognosis of changes

The Khanty-Mansi Autonomous Okrug –Yugra (KhMAO) locates in the central part of the West Siberian Lowland. It extends from the eastern macroslope of the Ural Mountains eastwards almost to the banks of the Yenisei River and from the Siberian Ridges in the north to the Kondinskaya taiga in the south (between 58° and 66° N). The mountainous part occupies about 6% of the area, the plain is flattened and heavily swamped (Atlas..., 2004). The area is located within the temperate climate zone. The northwestern part of KhMAO belongs to the Atlantic-Arctic region, the rest of the territory, to the continental West Siberian northern and central region (Natsional'nyi atlas..., 2007). The climate is humid with moderately warm summers and moderately severe snowy long winters, snow cover stays for a long time (several months).

According to meteorological observations analyzed for 1960–2021, the average annual air temperature is increasing throughout the entire territory as 0.33–0.52 °C/10 years. Changes in seasonal temperature are most pronounced in spring: from 0.49 °C/10 years in Leushi settlement to 0.89 °C/10 years in Nizhnevartovsk city. The number of days with temperatures above +20 °C for the period 1960–2021 is increasing at all stations by an average of 2 days per 10 years. At the same time, the number of days with the air temperatures below –20 °C at all monitoring sites is decreasing as 3 days per 10 years in average, but not always statistically significantly.

Over the past 50 years, the annual amount of atmospheric precipitation in KhMAO was increasing at a rate of 3–15 mm/10 years. The maximum amount of daily precipitation can be significant, especially in the summer, reaching 70–90 mm or even more. In 1960–2020, the maximum "drought" interval (precipitation < 1 mm) averaged 16–19 days.

Not only extremely low temperatures (below –50 °C), but also extremely high temperatures (above +35 °C) are registered. Floods are the most destructive hydrometeorological phenomenon, but rain floods are less common. This relates to the specifics of the territory, which locates on the low plain at the confluence of the Ob and Irtysh rivers with asynchronous opening and prolonged floods (the height of the water rise can reach 8–10 m). In general, this territory is characterized by high swampiness.

The area is characterized by dangerous phenomena associated with high temperatures and aridity. The area affected by fire can reach 120–140 thousand hectares annually. Strong winds and hurricanes are recorded almost throughout the entire territory of KhMAO; they may last 2–3 hours with the wind speed of 20–34 m/s.

³ Order of the Ministry of Natural Resources of Russia dated March 24, 2020 No. 162 "On approval of the List of wildlife species listed in the Red Book of the Russian Federation" (Registered with the Ministry of Justice of Russia on April 2, 2020 No. 57940).

⁴ Protected natural areas of Yugra. Specially protected natural areas of Yugra. Official website of the Department of Specially Protected Natural Areas of the Forestry and Specially Protected Natural Areas Department of Subsoil Use and Natural Resources of the Khanty-Mansi Autonomous Okrug – Yugra. Web page. URL: <https://ugraopt.admhmao.ru/> (accessed: 27.02.2023).

According to the climate risk assessment for KhMAO climate change adaptation plan⁵, seven phenomena (landslides, suffusion, sheet and gully erosion, flooding, hurricanes, tornadoes and strong winds, heat, drought) periodically reach catastrophic levels, while the hazard levels for drought, flooding, strong winds, precipitation, and fire hazard may be underestimated (Lipka et al., 2023).

Although floods are the most significant hazardous phenomenon in the region, the vulnerability of ecosystems to climate change is primarily associated with forest fires, to a lesser extent, with wind events and biogenic factors (Tretii otsenochnyi doklad..., 2022).

According to Russian Federal Service for Hydrometeorology and Environmental Monitoring (Rosgidromet), hazardous hydrometeorological events have damaged the population health and the economy in KhMAO 98 times since 1991 (Shamin et al., 2023). With a low average annual number, damage from one hazardous event can be recorded up to 5 times during the single year (Table 1), as the floods in 2015 (Shamin et al., 2023).

The most extreme years were 1993, 2006, and 2018 (Fig. 1).

The threshold values used by Rosgidromet for hazardous hydrometeorological phenomena (RD 52.88.699-2008⁶, RD 52.27.724-2019⁷) do not always correspond to the intensity and duration, at which they cause significant damage to particular species populations or lead to irreversible transformations of ecosystems over large areas. The database "Distribution of Hazardous Hydrometeorological Phenomena, Their Parameters and Consequences for Biomes in Russia" (Lipka, 2023) provides information on 22 categories of hazardous phenomena. Their parameters are obtained by the analysis of impacts on various components of natural systems: on entire ecosystem, on its structure and productivity, on the sensitivity of individual species of vascular plants and animals to certain weather and climate phenomena. For each hazardous phenomenon, two threshold levels are defined: (1) from the moment the first threshold is reached, it becomes dangerous for natural systems; (2) after exceeding the second threshold, the consequences become critical. In KhMAO, 19 phenomena reach the first threshold (15–17 for lowland biomes and 17–19 for orobiomes): very strong wind, tornado, very heavy rain, very heavy snow, large hail, severe blizzard, strong ice-rime deposits (including ice crust), severe frost, abnormally cold weather, extreme heat, abnormally hot weather, extreme fire hazard, avalanches, dry winds, atmospheric drought, high snow cover, flood, mudflow, and landslide. The second threshold is reached by 16 phenomena (10–11 on the plain and 15–16 in the mountains), extreme heat and atmospheric drought are excluded from the general list.

The modeled climate change forecasts based on the ensemble of global climate models evidence that by the end of the XXI century the average annual air temperature in the Western Siberia region will steadily increase by 2.6–6.8 °C compared to 1850s–1900s, depending on the scenario. An increase in maximum and minimum air temperatures by 2.4–7.3 °C, an increase in the continuous interval of days with maximum temperatures above +35 °C by 5–18, and a slight decrease in the maximum number of consecutive dry days are also possible (IPCC, 2021; Lipka et al., 2023). The speed of the strongest winds will increase by 1–3%. An increase in the amount of precipitation may be followed by an increase in the probability and severity of floods (IPCC, 2019; Tretii otsenochnyi doklad..., 2022).

As in most regions of Russia, KhMAO is expected to see a decrease in the probability of dangerous events associated with cold stress and an increase in events associated with high temperatures. Estimates of changes in the drought duration are ambiguous. An increase in the total amount of precipitation may be accompanied by an increase in daily maxima, which thus increases the prerequisites for rain floods (Lipka et al., 2023).

Biodiversity

The diversity of natural conditions is reflected in the presence of four biomes in KhMAO (Biomes of Russia, 2018). It is noteworthy that their boundaries on the plain (Fig. 2) do not coincide with the boundaries of climatic zoning (Natsional'nyi atlas..., 2007), although they belong to the same time period (the beginning of the XXI century). The boundaries of the orobiomes are close in configuration to that

⁵ Regional Plan for Adaptation to Climate Change in the Khanty-Mansi Autonomous Okrug – Yugra. (introduced by the Decree of the Government of the Khanty-Mansi Autonomous Okru – Yugra dated 08.12.2022 No. 659-p).

⁶ RD 52.88.699-2008. Regulation on the procedure for actions of institutions and organizations in the event of a threat of occurrence and occurrence of hazardous natural phenomena.

⁷ RD 52.27.724-2019. Manual on short-term general-purpose weather forecasts.

Table 1. Types and number of hazardous hydrometeorological phenomena that caused damage in KhMAO (according to: Shamin et al., 2023).

Hazard	Total number of events	Average number per year	Maximum number per year
Abnormally cold weather	4	0.13	2
Wind	24	0.75	4
Hail	4	0.13	4
Rain (heavy)	8	0.25	3
Complex of adverse events	3	0.09	1
Heavy shower	1	0.03	1
Blizzard	2	0.06	1
Low water level	1	0.03	1
Flood	4	0.13	1
Spring flood	9	0.28	5
Long-lasting heavy rain	2	0.06	2
Strong temperature decrease	3	0.09	3
Abrupt weather change	4	0.13	3
Severe frost	3	0.09	1
Heavy rime ice	1	0.03	1
Snow	6	0.19	3
Emergency fire risk	18	0.56	3

proposed for natural zoning of the Urals (Chibilev and Chibilev, 2012), belonging to the North Ural physical-geographical region (Eastern North Ural subregion) in the northern part of KhMAO and to the Middle Ural physical-geographical region (Eastern Middle Ural subregion) in the south.

The West Siberian northern forest-tundra-northern taiga (northern taiga) and middle taiga part of the Ob-Irtysh middle taiga-south taiga biome occupy most of the area. The southern taiga part of the Ob-Irtysh middle taiga-south taiga biome and the Middle Ural taiga (East Ural) biome, which are the richest in species diversity, cover less than 5% of the territory. The plant and animal diversity in KhMAO biomes is presented in Table 2.

According to the data of the Yugra Nature Supervision Agency, over 800 species of higher vascular plants are found in KhMAO (Doklad o sostoyanii..., 2017). In the publications, we have found over 1200 species of higher vascular plants, 571 fungi species, 973 lichen species, and 88 myxomycete species (Atlas..., 2004; Filippova et al., 2017; Krasnoborov et al., 2000).

The vegetation of the area is represented by the communities of forests, swamps, meadows, and mountain tundra (Atlas..., 2004). The northern taiga subzone is represented by West Siberian coniferous dwarf shrub-lichen-green moss sparse forests and woodlands; the moss cover growth there contributes to the swamping of the forests (Atlas..., 2004; Ogureeva et al., 1999). The middle taiga subzone is

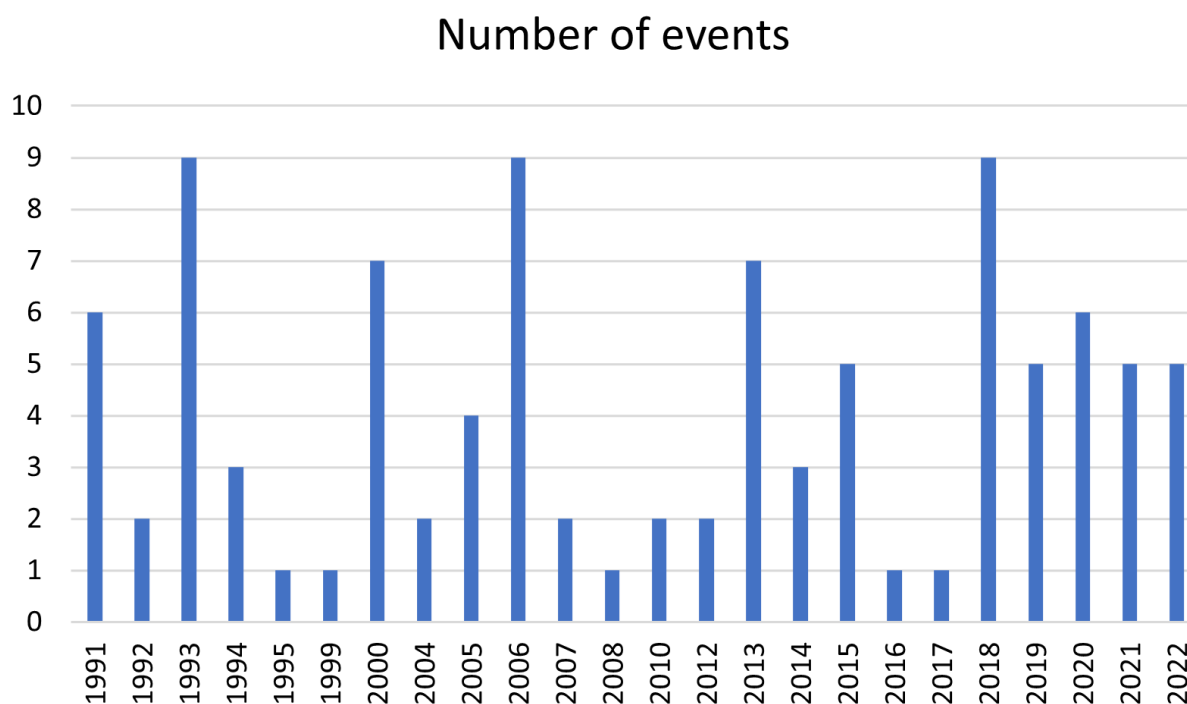


Fig. 1. Yearly dynamics of dangerous hydrometeorological phenomena that caused damage in KhMAO (according to: Shamin et al., 2023).

represented by West Siberian spruce-cedar and pine-green moss forests. Pine forests give way to dark coniferous forests when swamping increases; on sandy soils, they form pine forests with white moss. Meadow vegetation is confined to river floodplains and lowlands. Lichen communities used as reindeer pastures are widespread in the northern regions. A significant role is played by secondary dark coniferous-aspens-birch and birch-aspens forest communities that develop on the sites of burnt-out areas and clearings (Atlas..., 2004; Ogureeva et al., 1999). The southern taiga subzone is found only in the very south of the area; it is represented by West Siberian cedar-spruce-fir and pine forests with an admixture of linden (Atlas..., 2004; Ogureeva et al., 1999).

On the Ural Mountains within KhMAO, two zones are distinguished: subarctic (taiga) and boreal (taiga). Subarctic taiga is distinct by the total absence or insignificant role of closed forest communities. The leading role belongs to subarctic dwarf shrub tundra (Atlas..., 2004; Ogureeva et al., 1999). Subarctic communities include the northernmost and highest (within the region) part of the Ural Mountains (Atlas..., 2004; Ogureeva et al., 1999). Boreal taiga communities are distinguished by their leading role in the composition of mountain-taiga systems of coniferous Siberian forests. In the northern part of KhMAO, these are larch dwarf shrub-green moss forests; in the south, pine and larch sparse forests (Atlas..., 2004; Ogureeva et al., 1999).

The distribution of altitudinal zones in orobiomes on KhMAO is presented in Table 3. The vertical component for each zone does not exceed 500 m.

Waterlogging is a regional feature of KhMAO. One third of its territory is occupied by boglands, mainly of the raised and transitional type⁸. The development of boglands is facilitated by the flat relief, tectonic subsidence, poor drainage of the territory, excessive moisture, and low temperatures (Biodiversity..., 2020). The vegetation cover of the huge floodplains of the Ob and Irtysh rivers consists of many swamp, meadow, shrub and forest communities (Atlas..., 2004).

⁸ Resolution of the Governor of KhMAO – Yugra dated 25.01.2019 No. 2 “On the Forestry Plan of the Khanty-Mansi Autonomous Okrug – Yugra for 2019–2028”.

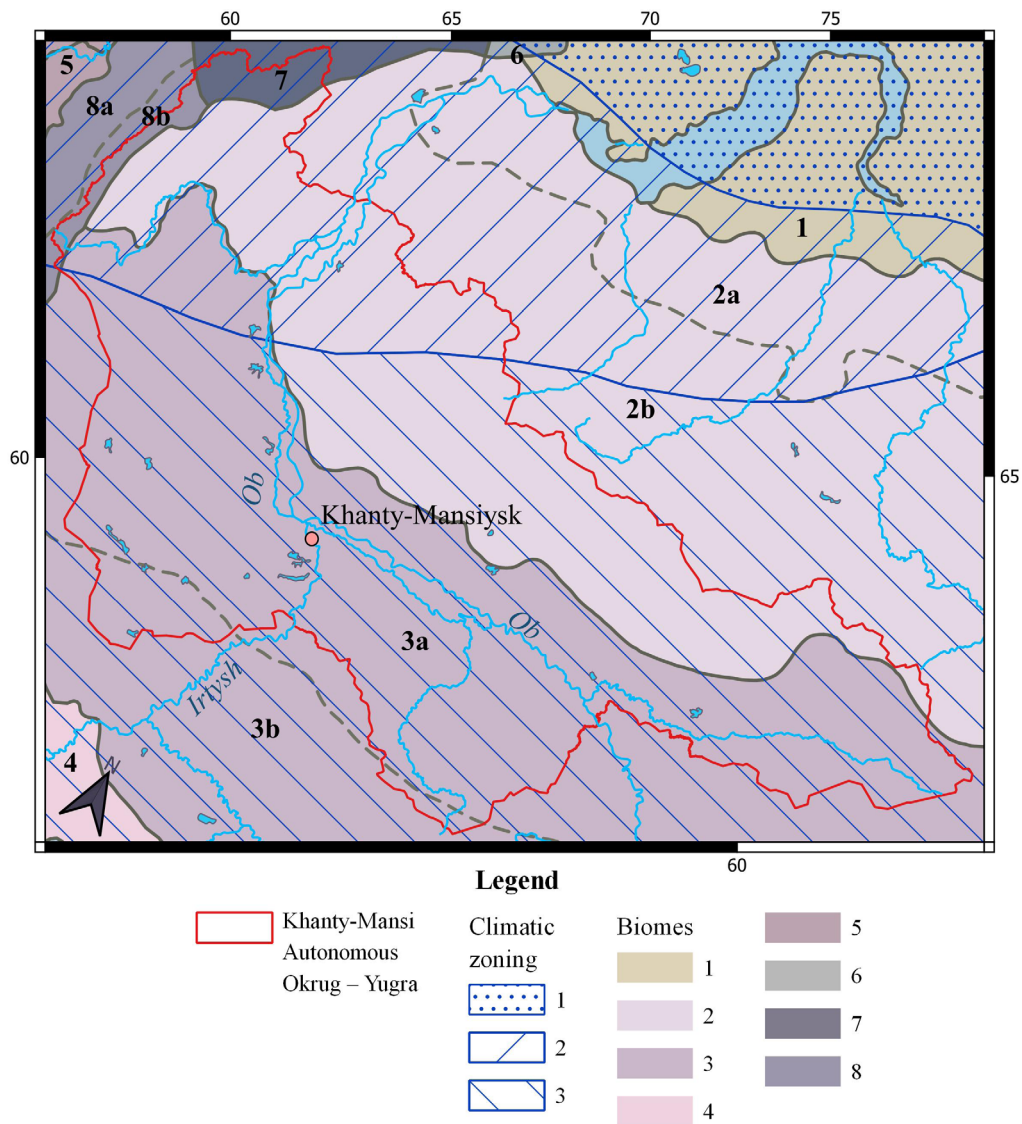


Fig. 2. Biome diversity and climatic zoning in KhMAO (based on: *Biomy Rossii*, 2018; *Natsional'nyi atlas...*, 2007). Climatic zones and regions: 1 – subarctic belt, Atlantic region; 2 – temperate belt, Atlantic-Arctic region; 3 – temperate belt, continental West Siberian region (northern and central subregions). Biomes: 1 – Kola-Bolshezemelsko-Tazovsky subarctic-tundra (southern subarctic-tundra); 2a – West Siberian northern forest-tundra–north taiga (forest tundra); 2b – West Siberian northern forest-tundra–north taiga (north taiga); 3a – Ob-Irtysh middle taiga–southern taiga (middle taiga); 3b – Ob-Irtysh middle taiga–southern taiga (southern taiga); 4 – West Siberian small-leaved forest; 5 – Trans-Ural middle taiga–southern taiga (Priuralsky); 6 – Central Siberian (arctic and subarctic tundra); 7 – Khibiny-North Urals subarctic taiga (Severouralsky); 8 – Middle Urals taiga: West Urals (8a) and East Urals (8b).

Table 2. Species diversity in biomes represented in KhMAO (according to: Biomy Rossii, 2018).

Biome	Vascular plants per 100 km ²	Number of species								% of the district's territory	% of biome
		Vascular plants	Bryophytes	Lichens	Mammals	Birds (nesting)	Reptiles	Amphibians			
Northern West Siberian forest-tundra–northern taiga (northern taiga)	300–400	600	300	500	41–45	136–150	1	3	37.2	36.8	
Ob'-Irtysh middle taiga–southern taiga (middle taiga)	300–400	900	300	500	41–45	151–165	3	4	56.4	54.8	
Ob'-Irtysh middle taiga–southern taiga (southern taiga)	400–500	1100	300	500	45–50	166–180	5	6	3.2	3.8	
Khibiny-North Ural hypoarctic taiga	300–400	550	400	900	31–35	151–170	0	1	1.7	25.0	
Middle Ural taiga	400–500	1650	450	240	51–55	196–210	6	3	1.2	9.3	

In KhMAO, the annotated list of animals has 1524 species and subspecies (as of 2011), including 66 mammal species, 256 bird species, 4 reptile species, 6 amphibian species, 29 bony fish species, 1 species of cyclostomes, and 1162 species of invertebrates⁹ (Doklad..., 2022).

In total, 35 species of flora and fauna listed in the Red List of the Russian Federation inhabit KhMAO, including 17 animal species and subspecies, 8 plant species and subspecies, 6 lichen species, and 4 fungi species. Mammals are represented by one species, Uralian beaver *Castor fiber pohlei* Serebrennikov, 1929; birds, by 14 species: black stork *Ciconia nigra* (L., 1758), red-breasted goose *Branta ruficollis* (Pallas, 1769), lesser white-fronted goose *Anser erythropus* (L., 1758), Bewick's swan *Cygnus columbianus bewickii* Yarrell, 1830, more spotted eagle *Clanga clanga* Pallas, 1811, pallid harrier *Circus macrourus* (S.G. Gmelin, 1770), golden eagle *Aquila chrysaetos* (L., 1758), white-tailed eagle *Haliaeetus albicilla* (L., 1758), osprey *Pandion haliaetus* (L., 1758), gyrfalcon *Falco rusticolus* L., 1758, peregrine falcon *Falco peregrinus* Tunstall, 1771, Siberian crane *Leucogeranus leucogeranus* (Pallas, 1773), Eurasian oystercatcher *Haematopus ostralegus* L., 1758, Eurasian eagle-owl *Bubo bubo* L., 1758; Pisces, by two species: Siberian sturgeon *Acipenser baerii* Brandt, 1869 and Siberian taimen *Hucho taimen* (Pallas, 1773). The plant species included into the red List, are arctic root *Rhodiola rosea* L., *Castilleja arctica* Krylov & Serg., Calypso orchid *Calypso bulbosa* (L.) Oakes, lady's-slipper *Cypripedium calceolus* L., narrow-leaved marsh orchid *Dactylorhiza traunsteineri* (Saut. ex Rchb.) Soó, ghost orchid *Epipogium aphyllum* Sw., moss grass *Coleanthus subtilis* (Tratt.) Seidl ex Roem. & Schult., lake quillwort *Isoetes lacustris* L. Vulnerable lichens are represented by tree lungwort *Lobaria pulmonaria* (L.) Hoffm., Scholander's rag lichen *Asahinea scholanderi* (Llano) W.L. Culb. & C.F. Culb., *Cetrelia alaskana* (C.F. Culb. & W.L. Culb.) W.L. Culb. & C.F. Culb., *Tuckneraria laureri* (Kremp.) Randle & A. Thell, mustard lichen *Pyxine soredata* (Ach.) Mont., arctic mushroom scales lichen *Lichenomphalia hudsoniana* (HS Jenn.) Redhead, Lutzoni, Moncalvo & Vilgalys, fungi, by witches' cauldron *Sarcosoma globosum* (Schmidel) Casp., *Gomphidius flavipes* Peck, reishi *Ganoderma lucidum* (Curtis) P. Karst., and wood cauliflower fungus *Sparassis crispa* (Wulfen) Fr. (Krasnaya kniga..., 2001, 2008).

The new approved list of wildlife species listed in the Red List of the Russian Federation contains information on 30 species and subspecies of animals inhabiting KhMAO⁹: these are mammals Eurasian beaver *Castor fiber* L., 1758 and Mednyi Island fox *Vulpes lagopus semenovi* Ognev, 1931; birds, ivory gull *Pagophila eburnea* (Phipps, 1774), taiga bean goose *Anser fabalis fabalis* (Latham, 1787), azure tit *Cyanistes cyanus* (Pallas, 1770), yellow-breasted bunting *Emberiza aureola* Pallas, 1773, rustic bunting *Emberiza rustica* Pallas, 1776, black stork, Baikal teal *Sibirionetta formosa* (Georgi, 1775), red-footed falcon *Falco vespertinus* L., 1766, red-breasted goose, horned grebe *Podiceps auritus* (L., 1758), lesser white-fronted goose, white-headed duck *Oxyura leucocephala* (Scopoli, 1769), greater spotted eagle, pallid harrier, golden eagle, white-tailed eagle, osprey, gyrfalcon, peregrine falcon, Siberian crane, willow ptarmigan *Lagopus lagopus rossicus* Serebrowski, 1926, Eurasian oystercatcher, and Eurasian eagle-owl; fish, nelma *Stenodus nelma* (Pallas, 1773), Siberian sturgeon, and Siberian taimen; and invertebrates, Apollo *Parnassius apollo* (Linnaeus, 1758), *Carabus (Carabus) menetriesi* Hummel, 1827. Therefore, in comparison with the Red List of the Russian Federation (Krasnaya kniga..., 2001), the number of Red List species of federal significance in KhMAO has 13 more taxa.

The Red List of the Khanty-Mansi Autonomous Okrug – Yugra includes 265 species of flora and fauna: 48 animal species (10 of mammals, 26 of birds, 3 of amphibians, 2 of bony fishes, 7 of invertebrates), 150 species of higher vascular plants (phanerogams), 29 lichen species, and 38 fungi species (Krasnaya kniga..., 2013).

Climate-induced transformation of elements of natural systems according to observation data

In modern literature, the number of examples, when the changes in natural systems are significantly associated with climate change or hazardous hydrometeorological phenomena, is still small. They are still fragmentary for each individual region. Nevertheless, the data is continuously accumulating in the publications; in particular, it is noticeable when comparing the chapters "Natural Terrestrial Systems" in the Second (Vtoroi..., 2014) and Third (Tretii..., 2022) assessment reports on climate change for the Russian Federation.

⁹ Protected Areas of Yugra. Specially Protected Natural Areas of Yugra. Official website of the Department of Specially Protected Natural Areas of the Forestry and Specially Protected Natural Areas Department of Subsoil Use and Natural Resources of the Khanty-Mansi Autonomous Okrug – Yugra. Web page. URL: <https://ugraopt.admhmao.ru/> (accessed: 27.02.2023).

Table 3. Distribution of altitudinal vegetation zones in biomes (according to: Biomy Rossii, 2018).

Altitude	Khibiny-Northern Ural hypoarctic taiga mountain-biome	Middle Ural taiga mountain-biome
2000 m	Nival	
	Golets-tundra	Golets-tundra
1500 m		
1000 m	Alpine tundra (low-shrub, lichen, moss)	Alpine tundra (low-shrub, lichen, moss)
	Birch open forest	Birch open forest
500 m	Light forest and creeping vegetation (yernik, alder, willow)	Larch-spruce, spruce forest
	Dark coniferous forest	Pine, larch-pine forest

Changes in the timing of phenological events are closely related to that in the seasonal air temperature. With the observed increase in latter, spring events in KhMAO shift to earlier dates, and autumn events shift to later dates, but weather conditions of a particular season of a particular year may contradict the general trend. A strong positive correlation ($R \geq +0.85$) is found between the transition of the average daily air temperature above $+10\text{ }^{\circ}\text{C}$ and the greening of birch. On average, the onset of phenological summer (blooming of rosehip and raspberry) is characterized by a positive correlation with temperature transitions above $+10\text{ }^{\circ}\text{C}$ and $+15\text{ }^{\circ}\text{C}$ ($R = +0.56\dots+0.95$). The onset of yellowing of birch leaves depends on the transition of average daily temperatures below $+5\text{ }^{\circ}\text{C}$ ($R = +0.61$), the end of leaf fall in birches strongly correlates with the establishment of the air temperatures below $0\text{ }^{\circ}\text{C}$ ($R = +0.81$) (Kuznetsova and Grebenyuk, 2015; Tretii otsenochnyi doklad..., 2022).

Due to the increase in average annual and seasonal temperatures, species populations inhabiting the southern limit of their distribution, including arctic fox *Vulpes lagopus* (Linnaeus, 1758), are gradually being replaced by more warm-loving species, for which the new conditions are more favorable (Vtoroi otsenochnyi doklad..., 2014).

For example, the wild boar *Sus scrofa* Linnaeus, 1758 is a completely alien species to the fauna of the Yugansky Reserve. This species started to penetrate here in the late 1980s (Yugansky Reserve, 2022). Daubenton's bat *Myotis (Myotis) daubentonii* (Kuhl, 1817) was first caught in KhMAO in 2005 (Krasnaya kniga..., 2013). The ranges of parti-coloured bat *Vespertilio murinus* Linnaeus, 1758, eastern water bat *Myotis (Myotis) petax* Hollister, 1912, and Daubenton's bat have also shifted northwards (Emtsev et al., 2012).

The expansion of the bird ranges northwards has been noted, for example, for the finches of genus *Carduelis* (Suldin, 2017), pallid harrier, and rock dove *Columba livia* J.F. Gmelin, 1789 (Emtsev et al., 2012). Pallid harrier was included in the Red List of KhMAO only in 2013, since this species had never been encountered here before (Krasnaya kniga..., 2013). Since 2000, in the "Samarovsky Chugas" Nature Park and adjacent territories, seven species of birds have been identified that came from the south as their range limits were expanding: Eurasian bittern *Botaurus stellaris* (Linnaeus, 1758), Baillon's crane *Zapornia pusilla* (Pallas, 1776), paddyfield warbler *Acrocephalus agricola* (Jerdon, 1845), common moorhen *Gallinula chloropus* (Linnaeus, 1758), great crested grebe *Podiceps cristatus* (Linnaeus,

1758), black tern *Chlidonias niger* (Linnaeus, 1758), and common blackbird *Turdus merula* Linnaeus, 1758. It cannot be ruled out that the presence of some of them is due to the poor studies of this territory earlier. In addition to the above-mentioned bird species, there are also species that have been previously found here as rare vagrant birds from the south; recently, they become more common, although these species do not nest here: mute swan *Cygnus olor* (J.F. Gmelin, 1789), western marsh harrier *Circus aeruginosus* (Linnaeus, 1758), Eurasian blue tit *Cyanistes caeruleus* (Linnaeus, 1758), gray heron *Ardea cinerea* Linnaeus, 1758 (Bochkov, 2022). In the southern part of KhMAO, the ranges of some rare reptiles are also expanding; for example, this is the common European viper *Vipera berus* (Linnaeus, 1758), its range expanding is associated with changes in temperature conditions (Starikov et al., 2011).

Simultaneously with the increase in water temperature, areas with favorable conditions expand for the parasite fauna of fish, so fish diseases such as diplostomoses, ligulosis, diphyllbothriasis, and that caused by cestodes of genus *Pteocephalus* (Avrunev et al., 2016) shift their range limits northwards.

The ranges of ground beetles may be divided into two clusters: "northern" (Yamalo-Nenets Autonomous Okrug, Subpolar and Northern Urals, KhMAO) and "southern" (Novosibirsk Region, Southern and Middle Urals, as well as Tyumen Region without autonomous districts). These ranges have a conditional border running between the southern and middle taiga of the forest zone within the administrative boundaries of KhMAO. As the biome boundary shifts, one can also expect the changes in the complexes of ground beetles at these territories (Akopyan, 2015).

The ranges of forestry insect pests are also expanding northward; in addition, weather conditions that trigger outbreaks of conifer- and leaf-eating pests have become more frequent (Doklad..., 2021). In the future, it is possible that such dangerous pests as gypsy moth *Lymantria (Porthetria) dispar* (Linnaeus, 1758) will penetrate into the territory of Yugra from the south; its model climate-dependent range already covers the southern territories of KhMAO (Bogdanovich et al., 2023).

In 2017–2020, rare plant species were registered in KhMAO for the first time: leathery grapefern *Sceptridium multifidum* (S.G. Gmel.) M. Nishida ex Tagawa, moss grass, dark-fruited cotoneaster *Cotoneaster melanocarpus* G. Lodd., creeping lady's-tresses *Goodyera repens* (L.) R. Br., pisiform grass pea *Lathyrus pisiformis* L., inundated club moss *Lycopodiella inundata* (L.) Holub, and anomalous peony *Paeonia anomala* L. (Alekseeva et al., 2020). Their discovery may be associated with both changing climatic conditions and increased exploration of the territory.

Floods and natural fires are the most frequent dangerous phenomena that lead to a significant reduction in the population of individual animal species in KhMAO.

In the event of floods, even species accustomed to regular floods and high waters are at risk, such as Uralian beaver (Atlas..., 2004; Krasnaya kniga..., 2013) and smoothed newt *Lissotriton vulgaris* (Linnaeus, 1758) (Krasnaya kniga..., 2013). Floods affect also European badger *Meles meles* (Linnaeus, 1758) (Doklad..., 2021). In birds, high floods lead to the death of clutches of ground-nesting species such as Eurasian oystercatcher and Eurasian eagle-owl (Krasnaya kniga..., 2013), and corn crack *Crex crex* (Linnaeus, 1758) (Emtsev and Bernikov, 2017). In addition to physical death, changes in the food supply as a result of floods pose a threat (Akopyan, 2015). At the same time, prolonged high-intensity floods lead to the widespread distribution and increase in the number of muskrats *Ondatra zibethicus* (Linnaeus, 1766) (Avrunev et al., 2016) due to the expansion of their habitat.

Increased forest fires cause a decline in populations of sable *Martes zibellina* L., 1758 (Doklad..., 2021) and western capercaillie *Tetrao urogallus* (Linnaeus, 1758) (Emtsev et al., 2012). For a number of bird species, fires lead to habitat loss for many years (Krasnaya kniga..., 2013).

The greatest danger for reindeer *Rangifer tarandus* (Linnaeus, 1758) is posed by an increase in the frequency and intensity of thaws and frosts, as well as high snow cover, sometimes reaching 75–90 cm (Avrunev et al., 2016; Pereyaslovets et al., 2019; Vtoroi otsenochnyi doklad..., 2014; Yuganskii Zapovednik, 2022).

Moose *Alces alces* (Linnaeus, 1758) suffer greatly from blood-sucking insects during the period of midge activity. Horseflies are of particular concern, damaging the skin of these ungulates and leaving long-lasting wounds. The most vulnerable parts of the moose are the belly and the back of the legs, where horseflies sometimes cause significant damage (Yuganskii Zapovednik, 2022). Rising summer temperatures are a factor favorable for the activity of blood-sucking insects.

Of the rare species listed in the Red List of KhMAO (2013), 112 species are located near the northern border of their distribution, and 20 species, near the southern one. Wildfires are often cited as limit-

ing climate-related factors and as causing the destruction of habitats. Species that require high humidity (28 species) do not tolerate droughts well. In the Red List (Krasnaya kniga..., 2013), changes in the hydrological regime of the area are considered only as a result of direct anthropogenic intervention; this phenomenon was not considered in the region as a consequence of changes in climatic conditions. Cold is indicated as a limiting factor for 12 species, high floods, for 8 species. Extremely high temperatures, as well as mudflows, water-rock flows, landslides and avalanches that transform habitats in the Ural Mountains, were not assessed as limiting factors.

Forecasts of changes in natural systems

Traditionally, it is believed that a change in air temperature at the Earth's surface by 1 °C approximately corresponds to a 1°-latitude shift of the climatic zone. The altitudinal gradient in different mountain systems is 0.5–1.0 °C per 100 m ascent/descent (Khromov and Petrosyants, 2012). The absolute increase in annual precipitation is 61 mm per 100 m of altitude for the Middle Urals (Berseneva and Danilova, 1954).

Since 1960, the average annual temperature has increased by 1.98–3.12 °C, and since the beginning of the XXI century, by 0.66–1.04 °C. Accordingly, in the most general approximation, the climatic boundaries of biomes have currently shifted 73–111 km further north (Fig. 3) than proposed earlier (Biomy Rossii, 2018). In the Ural Mountains, warming has led to a shift in the boundaries of altitudinal vegetation belts by 33–100 m, depending on microclimatic conditions. However, even minor changes

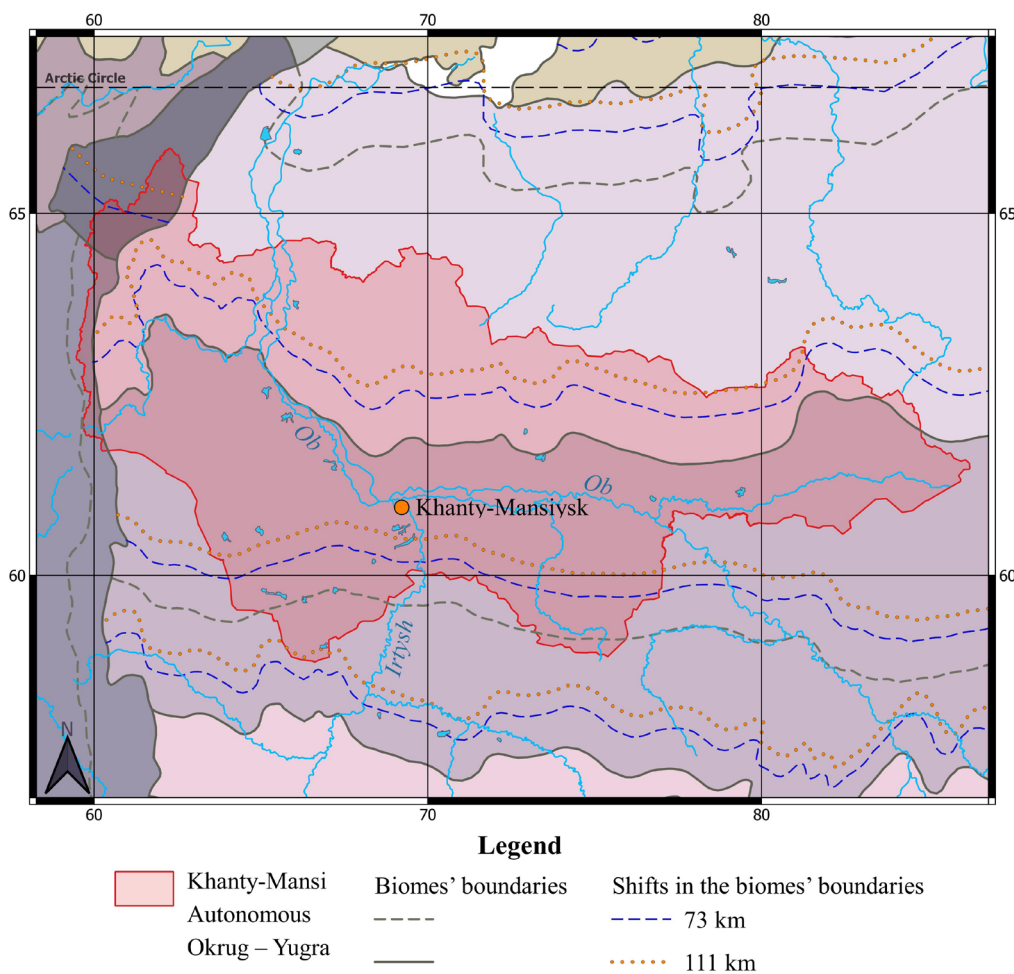


Fig. 3. Theoretical range of shifts in climatic conditions corresponding to the biomes' boundaries late XX – early XXI centuries.

lead to a significant reduction in the distribution conditions of the northern taiga and an expansion for southern taiga vegetation. The climatic boundary of the West Siberian southern small-leaved forest biome has approached the boundary of KhMAO (Fig. 3). In the mountains, the vertical component of vegetation belts does not exceed 500 m, in some cases, it is less than 200 m. Accordingly, the shift of climatic boundaries can be from 13–21% to almost 50% of the altitude component.

Methods of bioclimatic modeling are applied for more accurate forecasting of changes in biome boundaries due to climate change, including information on changes in the humidity of the territory, wind conditions and other parameters. According to the probabilistic forecast of the change of modern biomes based on climate indicators (Anisimov et al., 2017), the probability of a shift of climatic zonal boundaries to the north is 80–100% on the plain and about 3% for the mountainous part of KhMAO to the middle of the XXI century.

Comparing the results obtained using different techniques are difficult due to mismatch between the periods, the selected climate change scenarios, and the classifications of natural systems used. Table 4 shows the correspondence between the names of natural systems obtained by three different bioclimatic models covering the territory of Western Siberia (Bartalev et al., 2016; Rumyantsev et al., 2013; Zhiltsova and Anisimov, 2015) and the biomes proposed (Biomy Rossii, 2018).

The changes in vegetation in Russia for the next century have been forecasted (Bartalev et al., 2016) using four scenarios of changes in representative concentrations of greenhouse gases (RCP) in the atmosphere, proposed by the Intergovernmental Panel on Climate Change (IPCC) for the fifth cycle

Table 4. Titles of natural systems for bioclimatic modeling, used also for the map "Biomes of Russia" (Biomy Rossii, 2018).

Biomy Rossii, 2018	Bartalev et al., 2016	Zhiltsova and Anisimov, 2015	Rumyantsev et al., 2013
Northern West Siberian forest-tundra–northern taiga (northern taiga)	Бoreal coniferous evergreen forests	Northern taiga	Northern taiga
Ob'-Irtysk middle taiga–southern taiga (middle taiga)	Boreal coniferous evergreen forests	Middle taiga	Middle taiga
Ob'-Irtysk middle taiga–southern taiga (southern taiga)	Boreal coniferous deciduous forests + Boreal small-leaved deciduous forests	Southern taiga	Southern taiga
Southern West Siberian small-leaved forests	Boreal small-leaved deciduous forests	Mixed forest	Hemiboreal forest (mixed forests)
Tobolo-Priobskiy forest-steppe	Herbaceous vegetation and tundra	Steppe	Forest-steppe
Khibiny-Northern Ural hypoarctic taiga (Northern Ural)	Boreal coniferous evergreen forests	Alpine tundra	Mountains (no analysis)
Middle Ural taiga (Eastern Ural)	Boreal coniferous evergreen forests	Mountain taiga	Mountains (no analysis)

of assessment reports (IPCC, 2014a): RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 (Moss et al., 2010). The HadGEM-2-ES earth system model and the vegetation classification embedded in it (Jones et al., 2011) has been applied: the boreal zone is not subdivided into northern, middle and southern taiga biomes and represents a single zone of coniferous evergreen forests, which also covers the altitudinal zonation zone of the Urals. The steppe zone is defined as the "herbaceous vegetation zone" and is combined with the tundra (Table 4). According to the results of this forecast for the mildest climate change scenario RCP 2.6, a reduction in the area of boreal coniferous evergreen forests is expected, most of which will be displaced by small-leaved deciduous forests. In addition, an advance of the broad-leaved forest and steppe zone is observed in the southern regions of KhMAO. Forecasts for scenarios RCP 4.5 and RCP 6.0 suggest a distribution of biomes quite similar to the RCP 2.6 scenario, except the expansion of coniferous deciduous forests and a partial advance of the herbaceous vegetation zone in the eastern areas of KhMAO. Under the most severe climate change scenario RCP 8.5, boreal forests will be completely displaced by temperate broad-leaved forests (Table 5).

In order to predict potential changes in vegetation zoning in 2016–2045 and 2031–2060 (Zhiltsova and Anisimov, 2015), earlier climate change scenarios (Meehl et al., 2007) were applied. For scenario A2 (one of the most severe), the climate will favor a change in the dominant ecosystems in most of the boreal zone in KhMAO in the first half of the XXI century. A noticeable reduction in the taiga zone and a shift of its subzone boundaries northwards are potentially expected on the plain areas. The northern taiga will replace the forest-tundra and shrub tundra zones, so this zone would disappear completely from KhMAO territory (Zhiltsova and Anisimov, 2015). The middle taiga will locate entirely beyond the current boundary of the permafrost distribution area; by 2031–2060, the southern taiga zone and part of the mixed forests will be north of this boundary according to proposed climatic conditions. In this forecast (Zhiltsova and Anisimov, 2015), the area of altitudinal zonation, referred to mountain taiga (Table 4), will noticeably shrink and will be replaced in the lower belts by vegetation of the corresponding biomes of flat terrain (Table 5).

The forecast of possible changes in the zonal boundaries of vegetation in European Russia and Western Siberia in 2046–2065 (Rumyantsev et al., 2013) is also based on the hard scenario A2 (Kislov, 2011; Kislov et al., 2011). The results of the NCAP/NCEP reanalysis from 1961 to 1989 were used as the background period of the "modern climate" (Kislov, 2011; Kislov et al., 2011; Toropov, 2006). According to the modeling results, a shift in the boundaries of taiga subzones is expected in KhMAO, accompanied by the disappearance of climatic conditions suitable for boreal coniferous evergreen forests. Milder climatic conditions suitable for the mixed forest zone or sub-taiga will form in the central and southern parts of KhMAO. The vegetation of the southern areas will be transformed into forest-steppe within the Kondinsky District and southern Surgut District of KhMAO (Rumyantsev et al., 2013).

Table 5 summarizes the data on the predicted transformation of climatic conditions of biomes in KhMAO – Yugra in comparison with their current position, taking into account certain periods.

Global forecast of climate-driven transformation of terrestrial biomes by 2100 suggests a change from modern boreal evergreen (coniferous) and mixed forests to temperate deciduous forests with the participation of boreal mixed forests and forest-steppe in the south (Sato and Ise, 2022). The climate scenarios RCP 2.6 and RCP 8.5, the climate models Had2GEM-ES and MIROC-ESM were used, their results were integrated into the bioclimatic model CNN (Sato and Ise, 2022). The obtained forecast is closest to the estimates of S.A. Bartalev et al. (2016). Comparison with data on the biological diversity of modern biomes in KhMAO (Biomy Rossii, 2018) suggests that the transformation of ecosystems in response to climate change by the end of the XXI century will contribute to an increase in the total number of animal and plant species, since the biological diversity of the southern taiga biomes is higher than that of the northern taiga (see Table 2).

The issue of the response rate of ecosystems and their individual components to observed and projected climate change requires additional studies. Currently, desynchronization is occurring: more mobile species and the species with a higher reproductive rate adapt faster (IPCC, 2022). Not only suitable climatic conditions, but also seed transport, permafrost degradation, and many other factors are necessary for broadleaf forests to develop in place of boreal forests, as well as taiga communities in place of tundra ones. The system of direct and feedback links is complex and sensitive to direct anthropogenic impacts: nature management regime, pollution, fires, etc. (Olson, 2011).

Table 5. Predicted change in climatic conditions of biomes relative to their current geographic location.

Biomy Rossii, 2018 (at the beginning of the 20th century)	Bartalev et al., 2016 (by 2100)	Zhiltsova and Anisimov, 2015 (by 2031–2060)	Rumyantsev et al., 2013 (by 2046–2065)
	RCP 2.6 – boreal coniferous evergreen forests		
Northern West Siberian forest-tundra–northern taiga (northern taiga)	RCP 4.5, RCP 6.0 – boreal coniferous evergreen forests + boreal coniferous deciduous forests	Middle taiga + southern taiga	Middle taiga + southern taiga
	RCP 8.5 – broadleaf forests		
	RCP 2.6 – small-leaved deciduous forests		
Ob'-Irtysk middle taiga–southern taiga (middle taiga)	RCP 4.5, RCP 6.0 – small-leaved deciduous forests + broadleaf forests	Southern taiga + mixed forest	Southern taiga + hemiboreal forest (mixed forests) + forest-steppe
	RCP 8.5 – broadleaf forests		
	RCP 2.6 – small-leaved deciduous forests		
Ob'-Irtysk middle taiga–southern taiga (southern taiga)	RCP 4.5, RCP 6.0 – small-leaved deciduous forests + broadleaf forests + herbaceous vegetation	Mixed forest + steppe	Hemiboreal forest (mixed forests) + forest-steppe
	RCP 8.5 – broadleaf forests		
Southern West Siberian small-leaved forests	Broadleaf forests for all scenarios	Mixed forest + steppe	Forest-steppe + northern (herb bunchgrass) steppe + middle (dry) steppe

Biomy Rossii, 2018 (at the beginning of the 20th century)	Bartalev et al., 2016 (by 2100)	Zhiltsova and Anisimov, 2015 (by 2031–2060)	Rumyantsev et al., 2013 (by 2046–2065)
Tobolo-Priobsky forest-steppe	Broadleaf forests for all scenarios	Steppe	Northern (herb bunchgrass) steppe + middle (dry) steppe
Middle Ural taiga (Eastern Ural)	RCP 2.6 – boreal coniferous evergreen forests + boreal small-leaved deciduous forests RCP 4.5, RCP 6.0 – boreal small-leaved deciduous forests	Southern taiga	No analysis was performed
Khibiny-Northern Ural hypoarctic taiga (Northern Ural)	RCP 8.5 – broadleaf forests RCP 2.6 – boreal coniferous evergreen forests RCP 4.5, RCP 6.0 – boreal coniferous evergreen forests	Alpine tundra	No analysis was performed
	RCP 8.5 – broadleaf forests		

Conclusions

Current climate change in KhMAO is confirmed by observation data since the 1970s. In 1960–2021, the average annual air temperature in KhMAO increased by 0.33–0.52 °C/10 years, annual amount of precipitation, by 3–15 mm/10 years. The intensity of 19 hazardous hydrometeorological phenomena is sufficient to cause significant damage to natural systems, including irreversible changes.

The number of days with extremely low temperatures, the intensity and duration of cold waves decrease, but the minimum temperatures increase. The duration of periods with abnormally high temperatures increases; maximum temperatures in summer often exceed +25 °C. At the same time, there is an increase in the frequency and duration of both periods with heavy precipitation (more than 10 mm/day) and droughts (less than 1 mm/day).

Floods, droughts, and wildfires are the most common climate-related phenomena in KhMAO that can potentially cause mass death of animals, destruction of vegetation over a large area, or irreversible transformation of ecosystems. Over 25% of the area is subject to floods, and a process may last from less than 100 days to more than 200 (maximum 222 days), the development rate is 0.1–2.2 m/day. The number of consecutive days with low precipitation (less than 1 mm) is 16–20 annually. This level is sufficient for wildfires to occur. The critical threshold value of the Nesterov fire hazard index has been reduced in the region down to 6000 degree-days, the phenomenon can recur up to 3 times a year. The area covered by fire varies significantly, it may reach 120–140 thousand hectares in dry years. Strong winds are also common hazards, but they rarely reach hurricane force, and no statistical records of damage have been made. The impact of other climate-related hazards on natural systems may be understudied.

KhMAO is crossed by the boundaries of four biomes. Their biological diversity varies significantly and includes 600–1650 species of higher vascular plants, 31–55 species of mammals, and 136–210 species of nesting birds. More than 1200 species of higher vascular plants, 1571 fungi species, 973 lichen species, 1524 species and subspecies of animals (66 species of mammals, 256 species of birds, 4 species of reptiles, 6 species of amphibians, 30 species of fish-like animals) have been identified in KhMAO. In the regional Red List, 265 flora and fauna objects are listed: 48 species of animals (10 mammal species, 26 bird species, 3 amphibian species, 2 bony fish species, and 7 species of invertebrates); 150 species of higher vascular plants, 29 lichen species, and 38 fungi species.

Due to climate change, changes in phenological dates are confirmed, associated with an increase in the duration of the warm period. However, against the background of the general trend, weather conditions in the spring or autumn of a given year can be significantly colder, delaying or accelerating the onset of phenological events.

Field observations confirm changes in the ranges of 13 species, including new taxa for the area. In the mountains, woody vegetation moves up the slopes. Although climatic conditions no longer correspond to the biome boundaries of the late XX century, the transformation of ecosystems requires a longer period of time. Natural disasters can both accelerate and restrain the process.

The average annual air temperature is predicted to increase by 2.6–6.8 °C depending on the chosen climate change scenario. The maximum and minimum air temperatures are likely to increase by 2.4–7.3 °C, the number of days with maximum temperatures above +35 °C will increase by 5–18, and the maximum number of consecutively dry days will slightly decrease against the background of a general increase in precipitation. However, with significant warming, the increase in precipitation will not be enough to compensate for the increase in evaporation, which may lead to the territory aridization.

By the middle and end of the XXI century, most of the area of lowland biomes will be located within more southern climate zones: sub-taiga, broadleaf forests, or even forest-steppe, depending on moisture conditions. In most cases, there will be a significant increase in biological diversity, since the flora and fauna of more southern biomes are significantly richer.

Gradual climate change is favorable for 112 rare species inhabiting the northern range limit. However, suitable habitats will shrink or disappear for 20 arctic species. Local endemic species in the mountains are also vulnerable, since their habitats can be destroyed as a result of dangerous hydrometeorological phenomena.

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