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RESEARCH ARTICLE

Observations of Climate Change Impacts on Terrestrial Ecosystems in Russia

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ABSTRACT

In Russia, the modern climate change manifests primarily as substantially increasing annual mean near-surface air temperature. Its rate is 2-2.5 times higher than for globe. The amount of precipitation in the most parts of the country is also growing, but the pattern is more heterogeneous. The annual number of dangerous hydrometeorological events causing damage has also increased by 2-3 times compared to the end of the 20th century. The following adverse events for terrestrial ecosystems are indicated in the literature most often: increase in seasonal temperatures, heat and cold waves, permafrost degradation, droughts and aridization, floods, hurricanes, dust storms, natural fires, coastal erosion, mudflows, landslides, avalanches, the invasion of alien species, an increase in outbreaks of pests and diseases. They manifest either as trends or as hazards. In this paper, occurrence of a negative event within the natural zone is verified using meteorological databases and special reports of Russian Hydrometeorological Service. Dangerous events are distributed unevenly throughout the country. For all zonal ecosystems (polar deserts, tundra, boreal forests, broadleaved forests, subtropical forests, steppes, deserts) and mountain ecosystems, the number of types for hazardous events exceeds the number of trends. For rivers and lakes, their number turned out to be equal, and for peatlands, the number of unfavorable trends turned out to be higher than dangerous events. The least number of negative trends is observed in deserts (2). In other types of ecosystems, 3-4 negative trends may appear simultaneously. The biggest number of hazards (9) is found in mountains, and almost the same number (8) in tundra, taiga and steppes. The minimum variety of considered hazardous phenomena is noted in peatlands.

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Introduction

IPCC Sixth Assessment Report [1] has confirmed: "It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. The likely range of total human-caused global surface temperature increase from 1850-1900 to 2010-201911 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is likely that human influence contributed to the pattern of observed precipitation changes since the mid-20th century and extremely likely that human influence contributed to the pattern of observed changes in near-surface ocean salinity. Mid-latitude storm tracks have likely shifted poleward in both hemispheres since the

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1980s, with marked seasonality in trends (medium confidence). Human influence is very likely the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979-1988 and 2010-2019 (decreases of about 40% in September and about 10% in March). Changes in the land biosphere since 1970 are consistent with global warming: climate zones have shifted poleward in both hemispheres, and the growing season has on average lengthened by up to two days per decade since the 1950s in the Northern Hemisphere extratropics (high confidence). Human-induced climate change is already affecting many weather and climate extremes in every region across the globe" [1].

Scientific reports based on numerous direct observations data have confirmed, that by 20th years of XXI century there is no place in whole Russia, where climate remains unchanged [1-5].

The annual number of dangerous phenomena on the territory of Russia, that can cause damage increased by 2-2.5 compared to the end of the last century [2]. Natural systems are adapted to regular adverse hydrometeorological phenomena. At the same time hazards exceed the limits of their adaptive capacity, at least for some elements. It takes years, and sometimes tens and hundreds of years, to restore the number of species, structure and productivity of ecosystems. With a sufficiently frequent repetition of dangerous phenomena, with the simultaneous or sequential manifestation of several (cascade effects local or regional levels), the complete restoration of natural systems becomes impossible. Some components can disappear, the structure of natural systems changes [5].

According to projections the territory of Russia is expected to have warming rate in 21st century significantly exceeds the average global warming for any of the IPCC considered scenarios. The change in precipitation will result in increasing at the main part of the Russian territory and especially in Arctic and decreasing in some parts in the south [1,3]. The changes vary from place to place significantly. Their impacts on terrestrial systems are different, include negative and positive effects.

Changes in mean climatic parameters determine the habitat suitability for species [5,6]. Climate driven hazards, which number and severity are growing over the world, can lead to mass mortality of organisms and dramatic, sometimes – irreversible, landscape transformation [3-5,7,8].

The aim of the paper is to observe historical and projected climate change impacts on terrestrial ecosystems in Russia at the level of nature zones and biomes.

Materials and Methods

Data on historical climate changes are published annually by Russian Hydrometeorological Service (Roshydromet) in reports on climate patterns [2]. Information on the observed impacts of climate change and its consequences on natural systems has been generally presented in the IPCC Six Assessment Report [5] and Roshydromet Third Assessment Report on climate change [3].

The most actual information on climate change projections is summarized in the IPCC Sixth Assessment Report [1], including an interactive Atlas, and Roshydromet Third Assessment Report [3]. More detailed information can be taken from reports and articles of specialized scientific institutes of Roshydromet [9-16] and the Russian Academy of Sciences. Interactive maps based on the results of calculations for global (CMIP5 [17] and CMIP6 [1] scenarios) and regional (CIMIP5 [18]) models are available on the web portal of the Roshydromet Climate Center [19]. The results are averaged over 85 administrative regions of Russia.

Meteorological primary data and information about observed hazards per administrative regions are available as a set of databases at RIHMI-WDC-Russian Hydro Meteorological Data Research Institute-World Data Center [20-23].

The taxonomy of natural zones is following 6th National Report to CBD [24] and IPBES Regional Assessment for Europe and Central Asia [6]. Basic information about the biomes of Russia corresponding to the climatic conditions of the end of the past-the beginning of this century is presented on the map "The Biomes of Russia" [25] and in the monograph "Russia's Biomes. Plain Biomes" [26]. A biome is considered as a large zonal ecosystem that combines a number of interconnected smaller ecosystems, and which reflects the interaction of regional biota with climate and landscape structure [25]. The total diversity of terrestrial ecosystems embraces 66 biomes (35 for plains and 31 for mountainous subregions) [25,26].

Some types of terrestrial systems are out of the concept of natural zones and biomes: peatlands, rivers, lakes and glaciers. Bogs and swampy areas occupy at least 8% of the territory of Russia (about 1.4 million km^2). There are more than 2.5 million rivers and 2.7 million lakes with a total water surface area of 408,856 km^2 in the territory of Russia [27]. The Glaciers of Russia database contains information about 22 glacier systems with 7478 glaciers, the total area of glaciation is 54,531 km^2 [28].

Results and Discussion

Climate change in Russia has its own characteristics. The rate of warming in Russia since the mid-1970s about 2.5 times higher than the global average. In most of our country, there is a trend towards an increase in annual precipitation at a rate of 2.2%/10 years (on average for the period 1976-2021), although in some areas (the center of the European territory of Russia, the north of Chukotka) their decrease was recorded. The dynamics of precipitation by season in different regions of Russia is even more variable. In addition, climate change is manifested in an increase in its “nervousness”, i.e. an increase in the number of extreme (anomalous) weather events and their consequences, such as heat waves, droughts, floods, wildfires, etc. by 1.5-2 times compared to since the end of the last century [2,3,8].

Living nature always strives to come into line with abiotic environmental conditions. Such processes are not going fast, but some are already being discovered. Numerous publications have appeared that testify to a change in the ranges of individual species, a shift in phenological dates [3,29,30], a change in primary productivity [31] and the "greening" of ecosystems [32,33]. Much less often, publications note a shift in the geographic boundaries of biomes: the advancement of forest vegetation into the tundra and to higher altitudes, and the expansion of the desert zone. For example, in Putorana mountains, a forest boundary has shifted 60-90 m vertically over the past 60 years [34] and 50 m in Khibiny mountains [31].

The responses of ecosystems to climate change largely contribute to their adaptation to new abiotic conditions, i.e. they can be considered as autonomous (i.e. without human participation) adaptations. In this context, it is relevant to analyze the adaptive significance of ecosystem responses (reorganizations) to climate change, as well as to identify directions and conditions for anthropogenic measures that promote such adaptations [3,35].

By the middle of the century, it is expected that biomes in Russia, on average, on 67% of the area of their modern territory, will be incompatible with weather and climatic conditions typical for the incidence of the century, i.e. be in the climatic conditions of other biomes [36,37].

The Sixth National Report to the Convention on Biodiversity [24] informs of the seriousness of the negative impacts of climate change on ecosystems. As an adaptation measure, following CBD [38], it was supposed to remove the anthropogenic load. The report proposed two lists of ecosystems: those requiring the removal of anthropogenic pressure to adapt to gradual climate change, as well as for the restoration of ecosystems exposed to dangerous climate-related phenomena. The classification of ecosystems of the upper level was used – zonal on the plains, mountains, swamps and water bodies. For them, the most significant negative effects were indicated, mainly based on historical climate changes [24].

The impact of climate change on natural systems was also considered in the IPBES report [6] as one of the drivers leading to a decrease in biological diversity and, in some cases, a reduction in the area of high-ranking ecosystems-Units of Analyzes. In contrast to the 6th national report, here the mountains are considered in more detail-at the level of altitudinal belts.

The third assessment report of roshydromet [3] analyzes the vulnerability of zonal ecosystems, altitudinal belts and biomes depending on primary data. Changes in boundaries, ranges of species, phenological features, productivity and vulnerability to adverse climate-related phenomena are analyzed. The vulnerability of ecosystems in the Russian regions to climate change is associated with biotic (outbreaks of insect pests and forest diseases) and abiotic impacts (forest fires, permafrost degradation, prolonged droughts and floods, extreme wind and snow-ice regimes) [3].

The publications highlight the following main factors of negative impacts on terrestrial ecosystems in Russia.

Polar deserts in High Arctic

Extremely cold conditions represented only on islands and archipelagoes. Polar deserts and tundra biomes experience the greatest increase in average annual and seasonal temperatures in Russia [2,3,11,13].

Coastal erosion of icy and sandy soils can reach tens of meters per year. For example, according to remote data observations, the area of Ushakov Island in the Kara Sea has decreased by 15.24% from 1986 to 2021. The ice bank retreated by 800 m on average along the entire perimeter of the island, maximum-up to 2.5 km [39]. The rates of coastal retreat of Aldger Island (Frantz Josef Land) is lower (up to 1.7 m/year), but also accelerated due to increase of the ice-free period duration [40].

The maximum wind speed on Severnaya Zemlya archipelago exceeds 15 m/s 5-15 days a year. On Franz Josef Land it can exceed 20-25 m/s, the number of days with a wind of 15 m/s or more reaches 25-50 days [2].

According to projections by the end of the century the conditions of the Arctic islands will become favorable for dense tundra vegetation [41]. Climate change, if the rate of warming does not slow down, is considered as the main threat to the existence of the polar bear. The situation is aggravated by environment pollution and human-wildlife conflicts [42].

Tundra

The rate of increase in the average annual temperature on Taimyr Peninsula in tundra zone exceeds 1°C/10 years. Warming is manifesting at almost the same rate on Novaya Zemlya archipelago and in North-Eastern Siberia. The temperature rising is the most active in spring and autumn [2]. In some areas of tundra and forest-tundra of European Russia and Western Siberia climatic conditions already correspond to more southern natural zones [3,43].

Positive impacts include increase in the length of the growing season for plants and the nesting season for birds. As a result, the productivity of vegetation is growing, the forest boundary is shifting to the north, the ranges of species are expanding, and the migratory routes of birds are changing [3,32]. The expansion of the range of the black goose from east to west reached hundreds of kilometers per decade and intensified with a decrease in the ocean ice cover [44].

The negative consequences include an increase in the frequency of climatic anomalies - winter thaws, summer frosts, and increase in precipitation, including in winter, which leads to the mass death of individual populations (for example, reindeer due to the formation of crust). Warming creates favorable conditions for expansion to tundra for boreal species: brown bear [32], lynx, elk, etc. [44].

Permafrost degradation leads to formation of thermokarst landforms, which are more active in areas with disturbed vegetation. In Yakutia, the depth of seasonal soil thawing increased from 0.7-0.8 m (1970s) to 1 m or more. As a result, soils are excessively moistened, lakes overflow, and summer floods intensify [3,45].

The entire Arctic coast is exposed to strong winds and storms. Hurricane-force winds (more than 32 m/s) are observed in the Novaya Zemlya archipelago and in Chukotka [2,46]. Droughts and fires are becoming regular in the tundra zone [3].

Taiga-boreal forests

Changes in temperature and precipitation patterns varies significantly over the country with a general trend to warming and increasing of heat waves by number. Draughts and floods happen every year, sometimes at the same place during one season [2,3,21-23].

The frequency, intensity and scale of forest fires, 90% of which, even in the most remote areas, are caused by human faults, have increased significantly. This process is exacerbated by the impact of climate change. According to official statistics from 2009 to 2020 the area of forest fires amounted to 43.945

million hectares (an average of 3.662 million hectares per year) [47]. According to satellite data, the figures are higher. Between 2001 and 2016 annually in Russia from 5 to 20 thousand forest fires were recorded, which damaged forests on an area from 5 to 20 million hectares per year [47,48]. About 10% of natural fires occur annually in Russia due to thunderstorms. In the north, their number reduce to 2% in the Murmansk region beyond the Arctic Circle [49].

The impact of forest fires on landscapes in permafrost zone is often accompanied by a cascade effect, when one adverse impact contributes or directly initiates the next one. Dramatic changes in the vegetation cover are followed by rapid changes in the temperature and hydrological regimes of soils and rocks, the state of the permafrost roof because of feedback mechanisms [44].

In recent decades an increase of forest ecosystems death due to squalls and tornados in the warm period has been revealed for the territory of Russia [50,51]. In some years, the area of wind damage in forests can reach 30% of observed forest fire area [52].

Outbreaks of insect pests and diseases of the forest are classified as biotic climate-related disturbances [53].

Under RCP 8.5 scenario, coniferous forests may disappear in the main part of the modern distribution in Russia by 2100, or their area will be significantly reduced [54]. In the boreal forests of the taiga zone due to the oppression of a cold-loving species indigenous ecosystems of dark coniferous taiga will increase the number of birch and aspen. Near the southern border of the coniferous-deciduous forests will decrease role of spruce [55].

Temperate broadleaved forests

Fires, storms and outbreaks of pests are as common in broadleaved forests as in taiga [3]. According to observations, there is an increase in aridity in summer in all zonal biomes [2,56].

Under RCP 8.5 scenario by 2100 the area of broadleaved forests will significantly expand in the middle and northern parts of European Russia. Oak, maple, ash, linden and other broad-leaved species will actively replace coniferous trees [54,55]. At the same time in the south of the natural zone processes of reforestation will intensify, including oak, linden, hornbeam, beech (in Siberia) [55].

Subtropical forests

Eastern Mediterranean type forests represented at Crimea Peninsular and lower most western parts of the Caucasus Mountains near the Black Sea. Two types of mixed and deciduous humid subtropical forests with evergreen elements grow in the Caucasus Mountains: Colchic in the west and Hyrcanic in the east [6,25].

For subtropical forests, there is an increase in the average and maximum temperatures, aridization, as well as in number of heat waves [6,57]. The combination of the risks of heat waves, forest fires, extreme rainfall, floods, mudflows, landslides, hurricane-force winds, including hazardous event complexes, indicates a high level of climate extremeness. Moreover, dangerous hydrometeorological phenomena causing significant damage have observed almost every year [6,12,16,23,57].

An example of the catastrophic consequences of an invasive species introduction is a box tree moth (*Cydalima perspectalis* Walker) in 2012. It has developed in an active pest outbreak in 2013, and expanded from common box (*Buxus sempervirens*) into an endemic relict box (*Buxus colchica*) in the wild. In 2015 it reached Abkhazia and Crimea, and has destroyed most *Buxus colchica* in the Caucasus Colchic forests [6,58].

Steppes and deserts

The first desert in Russia was formed in the 70s of the XX century as a result of overgrazing. Currently, climate change contributes to the strengthening of the process and excludes the restoration of steppe vegetation [59].

Steppe and desert biomes [25,26] are subject to heatwaves, droughts, and fires. Droughts, recurring since 2016, lead to the drying up of the soil cover, the appearance of dust storms, a large number of fires, and a significant reduction in pasture productivity, which is confirmed by the NDVI index [2,3,10,12,16,24]. Dangerous atmospheric droughts became more frequent during the growing season, and the dates of their start were shifted to earlier dates (on average, by one to two weeks) in most of the steppe zone [60].

Severe atmospheric and soil drought, excessive grazing pressure, locust infestation and winds over 20 m/s caused severe dust storms in 2020. The maximum area covered by the storm reached 11 million ha [61].

By the end of the XXI century climate change will affect the biodiversity of the steppe and desert ecosystems greatly transformed by economic activity. Climate aridity will increase in forest-steppe, steppe, and semidesert [55,62]. The area of the steppe zone in southern Siberia will increase by 30%, and the desert steppes-twice [55].

Mountains

The climate-induced shift of the vegetation belts up the slopes of the mountains leads to a reduction in its area even while maintaining its width [24].

Increasing the area of taiga belt up to 60-65% is expecting. Transformation of vegetation zones and reallocation altitudinal belts would reduce tundra vegetation and biodiversity [55]. For example, in continuing warming in Altai, high-altitude plant communities on relatively low ridges (2000-2700 m above sea level) can be completely replaced by forest vegetation [63].

In all mountain systems, there is a tendency to reduce the area of glaciers. On average, over the second half of XX century, it decreased by more than 20% [64]. The highest rates of decrease in the area of glaciers (by 60-70%) were noted for the Koryak highlands and the Orulgan ridge (Yakutia). Over the previous 30 years, there has been a significant reduction in glaciation in all major systems: in the Caucasus-by 17%, in Altai-27%, in Kamchatka-11% [65].

As a result of glacier degradation processes activation, moraine deposits destroy, glacial lakes can be drained, river flow increases and enriches with stone material. Slope erosion, rockfalls, and mudflows intensify [66]. Mudflows destroy vegetation in the material transit zone and can bury more than one meter of sediment in the accumulation zone. In areas of mudflow activity, vegetation does not have time to recover and remains in a state of constant disturbance [67].

Peatlands

Peatlands can be found in any natural zone and any mountain region in Russia [27]. As wetlands, they suffer first of all from warming and droughts. At the same time flood impact is not negative for many types of swamps [3,6].

The resilience of natural peatlands to climate change is based on their self-regulation, but this capacity is not unlimited. Substantial changes in peatland hydrology (by drainage), soil hydraulic properties (by long-term drainage), and peatland relief (by oxidation, subsidence and peat extraction) make spontaneous and supported recovery more and more complicated. In damaged peatlands, climate change is expected to increase the probability of catastrophic events, such as peat fires, erosion, and inundation [6]. Permafrost thawing intensifies swamping processes and changes the spatial structure of polygonal and hilly swamps. The likelihood of peat fires is increasing everywhere, especially in the case of abandoned drained peatlands [3,68].

Rivers, fresh and brackish lakes

For aquatic ecosystems climate change is manifested in change in runoff (annual, seasonal), feeding regime of rivers, increase in extreme floods and low water levels, etc. [3,8]. An increase in temperature leads to change in the composition and abundance of aquatic organisms, and the introduction of invasive species, which is observed. An increase in temperature in combination with eutrophication leads to a significant decrease in water quality. Some lakes in the Arctic drain as a result of permafrost degradation, and new lakes appear at the site of termokarst processes [3,69]. Lakes in the south, especially shallow and brackish ones, dry up and their level of mineralization increases [3,6].

Table 1 summarizes the impacts of negative climate-related factors on terrestrial ecosystems. To assess the vulnerability of each type of ecosystem, it is important to distinguish whether the negative effect is a manifestation of natural disasters (hazards) and their consequences, or a smooth but irreversible trend. Accordingly, two columns are allocated in the table for assessing the presence of a threat for each type of ecosystem.

Table 1: Number of averse impacts types per main terrestrial ecosystems: Negative trends and hazardous events.

Terrestrial Ecosystems	Polar Deserts		Tundra		Taiga		Broadleaved Forests		Subtropical Forests		Steppes		Deserts		Mountains		Peatlands		Water	
Adverse impacts	Trends	Hazards	Trends	Hazards	Trends	Hazards	Trends	Hazards	Trends	Hazards	Trends	Hazards	Trends	Hazards	Trends	Hazards	Trends	Hazards	Trends	Hazards
Seasonal temperature rising					1		1		1		1		1		1		1		1	
Heat waves				1		1		1		1		1		1		1		1		1
Permafrost degradation	1		1		1										1		1			
Cold waves		1		1		1										1				
Droughts and aridization				1		1	1	1	1	1	1	1	1	1		1	1	1	1	1
Floods				1		1		1		1		1				1				
Storms and tornados		1		1		1		1		1		1		1		1				
Dust storms												1		1						
Wild fires				1		1		1		1		1		1		1		1		
Coastal erosion	1	1	1	1		1		1		1		1		1		1				
Mudflows, landslides, avalanches																1				
Pests outbreaks and diseases					1	1	1	1	1	1	1	1			1	1			1	1
Invasive species	1	1	1	1	1		1								1		1		1	1
Total	3	4	3	8	4	8	4	7	3	7	3	8	2	6	4	9	4	3	4	4

For all zonal (polar deserts, tundra, boreal forests, broadleaved forests, subtropical forests, steppes, deserts) and mountain ecosystems, the number of hazardous events exceeds the number of trends. For rivers and lakes, their number turned out to be equal, and for peatlands, the number of unfavorable trends turned out to be higher than dangerous events. The least number of negative trends is observed for deserts [2]. In other types of ecosystems, 3-4 negative trends appear simultaneously. The biggest number of hazards [9] is manifested in the mountains, and almost the same number [8] in tundra, taiga and steppes. The minimum variety of considered hazardous phenomena is noted in peatlands (Table 1).

This does not mean that peatlands are less vulnerable in terms of the impact of hazardous phenomena. We are describing a variety of negative effects.

In figures 1,2 natural zones are ranked depending on the number of effects. Contours are obtained by combining the boundaries of the corresponding biomes within zones on the Russian Biomes map [24]. Wetlands and water bodies are not shown because of their size.

According to IPCC Sixth Assessment Report [1] conclusions, "global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades. Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and reductions in Arctic sea ice, snow cover and permafrost. Under scenarios with increasing CO_2 emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere. Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level [1].

Adaptation of ecosystems to climate change can be facilitated by human activity [5]. The process has not only conservation value, but is fundamentally

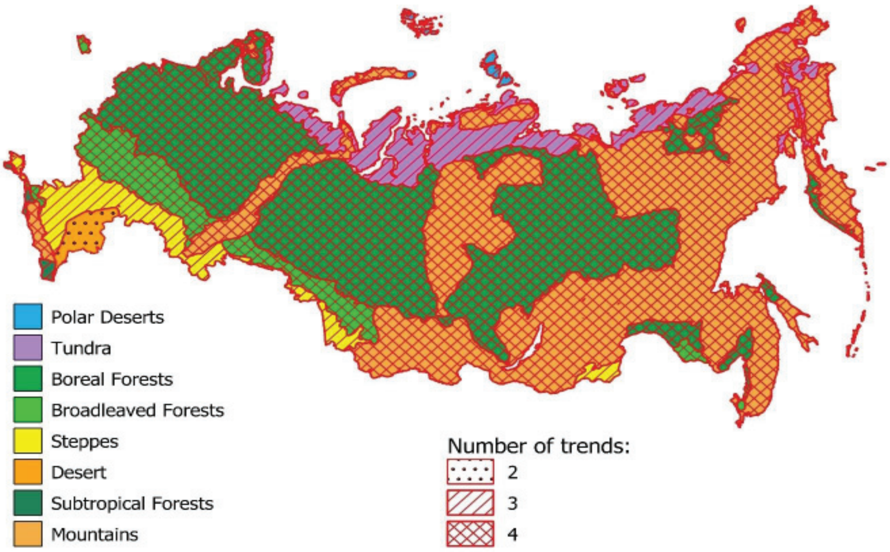

Figure 1 Adverse impact trends in natural zones: Colors: Natural zones and mountainous regions; Hatchings: Number of possible types of negative trends (Table 1).

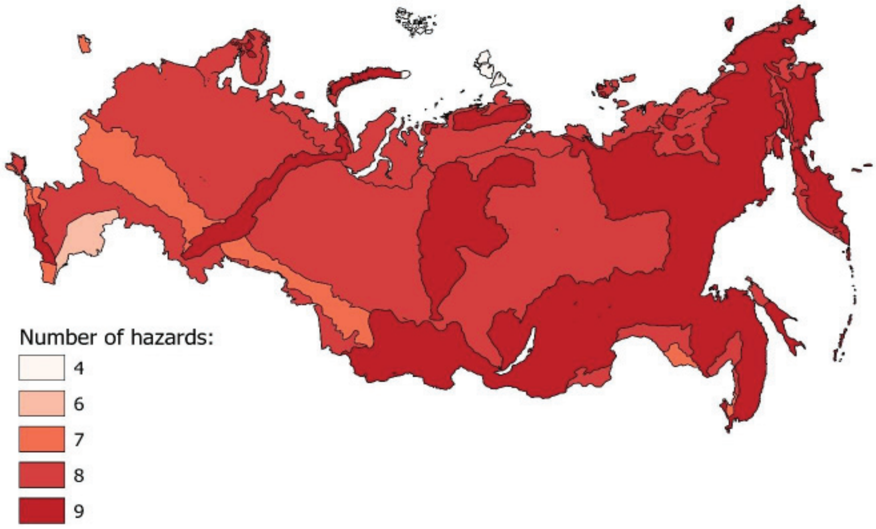

Figure 2 Number of possible types of hazards in natural zones (Table 1). The brightness of color reflects diversity of adverse impacts.

important for human wellbeing and renewable resources restoration. Mitigation activities to stabilize the climate system are implementing in parallel with adaptation in all countries under UNFCCC. Generally, adaptation gains some time for people to mitigate climate change. Without urgent mitigation we can meet the global lack of resources for adaptation.

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