Global climate change: wild fires and permafrost degradation in the Republic of Buryatia (Eastern Siberia, Russia)

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Abstract. On the territory of the Republic of Buryatia due to global climate change, significant transformations of the natural environment have been observed. Statistically significant trends of increase in temperature and decrease in precipitation with identification of wet and dry periods have been established. In the last 20 years due to the abnormally high air temperatures and the increasing aridity of the territory, the frequency and area of fires have increased, the rate of permafrost degradation on the southern boundary of the permafrost zone in the soils of meadow-steppe landscapes has increased twice.

1. Introduction
For the last half a XX century, global air temperatures have risen at a rate of ~ 0.2 °C per decade [1]. Climate changes affect global fire fluctuations [2] and may increase the number and size of fires in the coming decades [3]. Three intervals are distinguished: the warming in 1910–1945, a weak cooling in 1946–1975 and the most intense warming since the 1970s. In this regard, the purpose and objectives of these studies are to estimate the impact of global climate change on the transformation of the ecosystems of the Baikal region, in particular on vegetation and soil cover.

2. Models and Methods
The environmental conditions of the Republic of Buryatia (Eastern Siberia, Russia) are characterized by mountainous relief, a sharply continental climate, widespread seasonal freezing and permafrost, heterogeneity of parent material rocks and vegetation, a wide variety of soil cover [4]. The southern boundary of the cryolithozone stretches over the entire territory of the Republic (Figure 1) and modern global changes can cause the degradation of permafrost [5-7]. Permafrost, lithological and phytocenotic conditions are complicated when the relief is dissected. That is why different soils with sharply contrasting weathering and soil formation regimes are formed on the studied territory [8, 9].

Thus, Buryatia is characterized by an extremely unique combination of soil formation factors and is located on the southern boundary of permafrost distribution. Therefore, it is a convenient model for studying the atmospheric and soil climate and a quantitative estimation of processes of soil freezing and thawing due to global climate change.

Climate change monitoring of the southern boundary of the permafrost zone is carried out using the atmosphere and soil measurement complex (ASMC). ASMC is a development of the Siberian Branch
of the Russian Academy of Sciences [10]. ASMC conducts autonomous long-term interfaced measurements of atmosphere and soil meteorological parameters. To compare the soil climate, ASMC was established on different types of permafrost distribution (Figure 1): a) continuous — the central part of the Vitim Plateau (Turbic Cryosol Mollic, Bagdarin polygon, N 54°37'326", E 113°48'108", 947 m a.s.l.); b) discontinuous – the south of the Vitim Plateau (Haplic Chernozem Tonguic, Eravna test site, N 52°30'530", E 111°32'443", 933 m a.s.l.); c) sporadic – the north of the Selenginsk Middle Mountains (Natric Chernozem, Kizhinga test site, N 51°82'384", E 109°82'018", 726 m a.s.l.), the Eastern Baikal region (Entic Podzols, Goryachinsk test site, N 52°98'5606", E 108°28'4349", 502 m a.s.l.).

![Figure 1. The map of the distribution of the permafrost types [11] and the scheme of the atmosphere and soil measurement complex (ASMC) locations [12].](image)

A detailed soil characteristic was given earlier [12]. Turbic Cryosol Mollic is formed on the floodplain terrace under meadow grasses in the central part of the Vitim Plateau. These soils are characterized by a gray humus horizon, a light granular structure, a slightly acidic reaction, low humus, and moisture content. Permafrost is recorded at a depth of 1.90-1.95 m. Haplic Chernozem Tonguic can be found on the lakeside plain of the Eravinskaya hollow under meadow steppes. These soils are characterized by a loamy dark humus horizon with a high content of humus and a neutral reaction of the environment. Soil moisture content increases with depth. Permafrost is found at a depth of 2.75-2.80 cm. Natric Chernozem is formed on the gentle slope of the Kizhinginskaya hollow under cereal forb vegetation. These soils are characterized by a loamy granular structure and a high content of humus in the upper horizons, the middle horizon contains ions of Na⁺ as well as Ca²⁺ and Mg²⁺ in the composition of the soil-absorbing complex. The soils freeze seasonally at 2.40-2.45 m, remaining constantly thawed in the subsoil. Entic Podzols are found under pine-larch forests on the eastern coast of Lake Baikal. These soils are characterized by the coarse-humus horizon and a layer of up to 0.02 m of light gray bleached sand. Middle horizons B are represented by moist fine-grained sand, separated in color from brown to ocher-brown and density. Horizon C is at 0.41 (0.44) m and is characterized by moist, grayish-brown sand with fine gravel and small stones. The soils seasonally freeze at 1.60-1.65 m, remaining constantly thawed in the subsoil.
Thus, Turbic Cryosol Mollic and Haplic Chernozem Tonguic are formed in harsh climatic conditions (cold and long winter, short summer), Natric Chernozem — in a sharply continental climate with a cold winter and a dry short summer, and Entic Podzols — in a humid climate with relatively “warm” winter and “cool” summer with an abundance of precipitation in winter.

3. Results and Discussion

The collection and analysis of the parameters of the atmospheric climate show that changes in air temperature in Russia are more expressed than on the planet as a whole, and even more by 2.5 °C in Buryatia [13]. Quick warming in the Baikal and Transbaikalia is also emphasized by other researchers [14–16]. It should be mentioned that in the last decade the average annual temperature in Transbaikalia crosses the zero boundary, becoming positive which was previously noted occasionally.

Fluctuations in the amount of precipitation over the years are very significant, the difference reaches about 100-150 mm. In the city of Ulan-Ude with extremes of 413.3 mm (1959) and 109.6 mm (1989), the extreme amplitude is 303.7 mm. The variability of precipitation increases with time, i.e. the extreme conditions for this indicator increase. So, in the segment 1935-1942 the standard deviation of the annual precipitation amount was ± 32.2 mm, now the deviations from the climatic norm have become more extreme and the standard deviation is ± 65-83 mm, i.e. the deviations from the average long-term amount (256 mm) increased from 13 to 25-32 % (Figure 2).

Thus, on the territory of the Republic of Buryatia statistically significant trends of increase in temperature and decrease in precipitation with identification of wet and dry periods are established.

Due to global changes in the territory of the Republic of Buryatia significant transformations of the environment are observed. Over the last 20 years, the frequency and area of fires have increased due to the abnormally high air temperatures, the increasing aridity of the territories and the extremely high flammability of the prevailing light conifer tree species [17–21].

The analysis of the chronology of wildfires in the Republic of Buryatia from the 1960s shows a significant increase in their number and area from 1999 to the present (Figure 3). The increase in the number of wildfires from 1966 to 1996 occurred with a certain cyclical nature every 6-8 years old. In addition, there is an increase in the frequency of fires and their area over the last 20 years. In the period from 1966 to 1995, the fires covered about 360 thousand hectares of forests of Buryatia, which on average is almost 12 thousand hectares per one year. The increase in the area of fires in the period
from 1996 to 2016 compared to the previous period occurred almost 6 times. A maximum number of fires occurred in 2003 and of the area of forests in the fire occurred in 2015.

![Figure 3. Number (N) and area, ha, (S) forest fires in Buryatia from 1966 to 2016 [20].](image)

In spatial terms, the largest number and area of fires are recorded in the valleys of major rivers: the Selenga, the Uda, the Chikoi, the Irkut, and the Barguzin. It is here, along the river valleys and the slopes of the foothills, Arenosols are formed under pine forests on sandy and sandy-loam deposits. These landscapes have low water capacity and extremely high burning of forests, especially in the spring and summer period (April, May), when the moisture coefficient is 0.1–0.2 and corresponds to the values of semi-desert. The smallest numbers and areas of fires are observed on the ridges of the Eastern Sayans, the Khamar-Daban, and the Stanovoye Highlands. In these mountainous landscapes under dark-coniferous (cedar, spruce, fir) taiga and larch forests on Cambisols and Cryosols the maximum amount of precipitation falls.

At the suggestion of A P Chevychelov [22], fires can be attributed to the sub factor of soil formation which takes part in the formation of the soil profile of the taiga soils of Yakutia and Buryatia and changes their properties in landscapes at the taiga and steppe contact [23-27].

The analysis of post-fire soil successions of Arenosols, which are formed in pine forests on sandy deposits and peat lowland soils of the tectonic trough in the Selenga delta region of Buryatia, shows the following [27]. Under the influence of fires in Arenosols, charring, and ashing of organic matter occurs, the destruction of signs of podzolization. In the soil after the bottom fire, carbonaceous horizons of forest litter and humus are formed on the surface. Soil formation occurs under the canopy of a sparse adult stand without signs of renewal. After a top fire, the soil degrades completely, soil formation begins with a “0” moment, the natural restoration of forest vegetation is difficult. After fires on drained peat deposits, Sapric Histosols is transformed into pyrogenic formations - Gleysols Pyrogenic with a layer of loose ash. Peat horizons are burned completely with complete loss of carbon. Ash substances are actively carried away by water currents or wind; the stocks of ash elements are reduced by 10–15 times. The peat formation process is not resumed.

We noticed that climate change affects the depth of seasonal thawing in 1987 [28]. Subsequent studies confirmed this completely.

Climate warming and aridization affect the depth of thawing as an integral indicator of the thermal state of permafrost soils. In the landscapes of the south of the Vitim Plateau, over three-time cuts (1909, 1981 and 2008), the ambiguous reaction of the thickness of the seasonal soil thawing layer to global warming was established [28-29]. The maximum change in the soil thawing depth (by 1.4-1.7 m) over the 20th century was revealed for open steppe spaces. In landscapes of sedge-wilder swampy meadows, the changes in permafrost-thermal conditions are not recorded. In permafrost larch forests, the positive trend is poorly expressed (by 0.25–0.3 m).
Our instrumental data on the atmospheric climate and temperature regime of Haplic Chernozem Tonguic show that in the south of the Vitim Plateau (in the transition zone from continuous permafrost to the patchy one) there is a tendency to increase in average annual air temperature and decrease in precipitation. With such a tendency of the atmospheric climate in the studied soils, the long-term permafrost degradation by 50-70 cm is observed, the process rate of which from 1965 to 1975 was 1 cm/year. In the period from 1975 to 2015, the rate of degradation increased by almost 2 times 1.5-1.8 cm/year. The analysis of the soil temperature data currently indicates that the biologically active temperature (> 10 °C) began to penetrate down to 80-90 cm, which is 20-30 cm lower in depth than it was 50 years ago (Table 1).

| T, °C | The end of the 60s | The beginning of the 80s | Present days |
|------|-------------------|-------------------------|-------------|
|      | days | cm | days | cm | days | cm |
| 15   | 79   | 15 | 60   | 22 | 56   | 40 |
| 10   | 96   | 45 | 90   | 90 | 88   | 65 |
| 5    | 126  | 70 | 140  | 130| 127  | 130|
| 0    | 210  | 220| 185  | 240| 180  | 280|
| -2   | 205  | 300| 205  | 290| 212  | 300|
| -5   | 138  | 200| 158  | 200| 176  | 180|
| -10  | 112  | 150| 108  | 130| 140  | 99 |
| -15  | 80   | 65 | 69   | 95 | 89   | 71 |

4. Conclusion
On the territory of the Republic of Buryatia, the significant transformations of the natural environment caused by global changes are observed: statistically significant trends of increase in temperature and decrease in precipitation with identification of wet and dry periods have been established. In the last 20 years, the frequency and area of fires have increased due to the abnormally high air temperatures, the increasing aridity of the territory and the high burning capacity of pine forests.

In spatial terms, the largest number and area of fires are recorded in the valleys of large rivers, where Arenosols are formed under pine forests on sandy and sandy-loam deposits. These landscapes have low water capacity and extremely high flammability. The smallest numbers and areas of fires are observed on the ridges of the Eastern Sayans, the Khamar-Daban and the Stanovoye Highlands, where the maximum amount of precipitation falls in the mountain landscapes under dark coniferous taiga and larch forests on Cambisols and Cryosols.

Under the influence of fires on Arenosols in the Selenga delta area, charring and ashing of organic matter, the destruction of signs of podzolization occur. After a bottom fire soil formation occurs under the canopy of a sparse adult stand with no signs of renewal; after a top fire - soil formation begins with a “0” moment, the natural restoration of forest vegetation is difficult; after the fires on drained peat deposits Sapric Histosols peat formation process does not resume.

In the landscapes of the south of the Vitim Plateau, the maximum change in the thawing depth of frozen soils over the twentieth century was revealed for open steppe spaces; in landscapes of wetland meadows, changes in permafrost-thermal conditions are not recorded; in larch forests - a positive trend is weak. Over the last thirty years, the rate of degradation of permafrost in the soils of meadow-steppe landscapes has increased 2 times.

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Table 1. Duration (days) and depth of penetration (cm) of temperatures into the soil.

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