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Identifying Possible Climate Change Signals Using Meteorological Parameters in Short-Term Fire Weather Variability for Russian Boreal Forest in the Republic of Sakha (Yakutia)

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Abstract

The Boreal forest is a terrestrial ecosystem highly vulnerable to the impacts of short-term climate and weather variabilities. Detecting abrupt, rapid climate-induced changes in fire weather and related changes in fire seasonality can provide important insights to assessing impacts of climate change on forestry. This paper, taking the Sakha Republic of Russia as study area, aims to suggest an approach for detecting signals indicating climate-induced changes in fire weather to express recent fire weather variability by using short-term ranks of major meteorological parameters such as air temperature and atmospheric precipitation. Climate data from the "Global Summary of the Day Product" of NOAA (the United States National Oceanic and Atmospheric Administration) for 1996 to 2018 were used to investigate meteorological parameters that drive fire activity. The detection of the climate change signals is made through a 4-step analysis. First, we used descriptive statistics to grasp monthly, annual, seasonal and peak fire period characteristics of fire weather. Then we computed historical normals for WMO reference period, 1961-1990, and the most recent 30-year period for comparison with the current means. The variability of fire weather is analyzed using standard deviation, coefficient of variation, percentage departures from historical normals, percentage departures from the mean, and precipitation concentration index. Inconsistency and abrupt changes in the evolution of fire weather are assessed using homogeneity analysis whilst a Mann-Kendall test is used to detect significant trends in the time series. The results indicate a significant increase of temperature during spring and fall months, which extends the fire season and potentially contributes to increase of burned areas. We again detected a significant rainfall shortage in September which extended the fire season. Furthermore, this study suggests a new approach in statistical methods appropriate for the detection of climate change signals on fire weather variability using short-term climate ranks and evaluation of its impact on fire seasonality and activity.

Keywords

Boreal Forest Fires, Climate Change Signal, Short-Term Climate Variability, Fire Weather, Hydrometeorological Trends

1. Introduction

In this century the global climate has changed by an increase of mean temperature. For boreal areas, the Asian Development Bank notes, that warming is higher over higher latitudes in Asia, and projects that temperatures may rise by 2˚C - 8˚C in this century (ADB, 2017: p. 21). Because this increase has been noticeable since the 1970s, it has been possible to examine whether the changing climate has already affected the frequency and magnitude of recent forest fires. Due to this, scholars could establish relationships between meteorological conditions and fire occurrence (Pinol, Terradas, & Lloret, 1998). However, fire potential and fire behavior of individual fires during specific days or months are identified by fire weather (Liu, Goodrick, & Stanturf, 2013), which can be highly variable.

In this study, we aimed to develop an approach for detecting signals indicating changes in fire weather due to climate change to express recent fire weather variability and related changes in fire seasonality and activity. In doing so, we would like to cover three important fire ecology problems. The first hinges on the necessity for research devoted to the assessment of the impact of short-term and rapid climate changes on fire weather variability. Most of the existing research (Dupire, Curt, & Bigot, 2017; Freeborn, Jolly, & Cochrane, 2016; Jolly et al., 2015; Liu, Yang, Chang, Weisberg, & Hong, 2012) investigated the impact of climate change on fire weather variability using long-term ranks of meteorological parameters with durations of more than thirty years. The long-term averages may conceal climate changes that have appeared in more recent decades and may not detect the initial signal of rapid climate changes (Bateman et al., 2016; Farinotti, 2013). So, what do we know about the impact of more rapid climate changes on fire weather variability and how can we extract that climate change signals through widely used statistics and analytical techniques?

The second issue to be addressed is the examination of the fire weather changes during the entire fire season, including the onset, the peak fire period and the end of the fire season. And, third, how should these changes be explained in the areas most affected by modern climate change such as boreal forest ecosystems? To address these research questions, we selected as our study area, which is one of the most fire-prone regions of boreal Russia, the Republic of Sakha (Yakutia) situated in the Far East of the country.

Our previous research (Kirillina, Shvetsov, Protopopova, Thiesmeyer, & Yan, 2020) showed the extension of the fire season in the Sakha Republic, and related it to cumulative increases of the burned area in the region, during the period 1996-2018, showing the most significant, rapid increase in fire activity. Here, the study period 1996-2018, based on credible satellite burned area observations for the Republic (NOAA AVHRR and MODIS). We hypothesized that the reported changes were associated with the earlier coming of spring and the lengthening of fall which extended the duration of the fire season in the Republic. The extension of the fire season was correlated with the exponential growth in the extent of the burned area.

Moving from these two previous findings, the lengthening of the fire season and the increase of fire activity, in this current research we aimed to find both a broader relation to climate change and a more specific means of understanding this phenomenon through recent meteorological statistics and their analyses. Despite existing research describing both regional climate change (see Study Area description for details) and the impact of climate and weather changes on fire activity in the Sakha Republic, particularly historical changes in temperature and precipitation (Hayasaka, 2011; Kirillina, Goumehei, & Yan, 2016; Protopopova & Gabysheva, 2015), comprehensive research statistically demonstrating this impact still does not exist. Our selected study area has five forestry districts (these are the main administrative division of the Russian Forestry Service, on the territory of the Sakha Republic which has a total of nineteen forestry districts) that show significant increases in burned area. Each forestry district has one meteorological station. Due to the relatively small size of these forestry districts, their latitudes and longitudes as well as elevation and terrain do not vary much, so we used the data from each existing station per district to represent climate conditions of the forestry district where this station is located. However, our further purpose is for the presented methodology to be used for wider areas with more developed networks of hydrometeorological stations.

2. Data and Methodology

2.1. Study Area

The Republic of Sakha (Yakutia) is the largest region of the Russian Federation, occupying 40% of the territory of Eastern Siberia. The climate is sharply continental, which accounts for extreme temperature changes and low precipitation. Overall, little snow during winter, fast snow melting and dry spring seasons contribute to the naturally high forest fire risk in the region (Solovyev & Kozlov, 2005). The Republic suffers from persistent fire events (Protopopova & Gabysheva, 2016) and has one of the largest areas of burning in the country (Rosstat). Other factors, such as strong regional climate warming (Fedorov, Ivanova, Park, Hiyama, & Iijima, 2014; Kirillina & Lobanov, 2015; Kirillina, Lobanov, & Serditova, 2015) and the warming potential of the recent trend of rapid industrial development in the region make this study highly relevant.

More detailed information about the selected forestry districts is presented in Table A1 (**Appendix 1**).

2.2. Data Description

Air temperature and atmospheric precipitation data are obtained from the "Global Summary of the Day Product" of the US National Oceanic and Atmospheric Administration (further NOAA GSOD) for the period of 1996-2018 (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&resolution=40). As the reference stations, we used meteorological stations located in the five Yakutian forestry districts with significant increases of burned area (**Figure 1**). One meteorological station represents one forestry district (**Table 1**).

The monthly means of the air temperature from April to October, the annual averages, seasonal (May-October) and peak fire period (June-August) means were analyzed. As for atmospheric precipitation data, we used the monthly total precipitation from the months of April to October, the annual, seasonal and peak fire period means of total atmospheric precipitation. Further, we computed historical normals for 1961-1990 and for the most recent 30-year period (1989 to 2018) for comparison with climatological means for study period, 1996-2018.

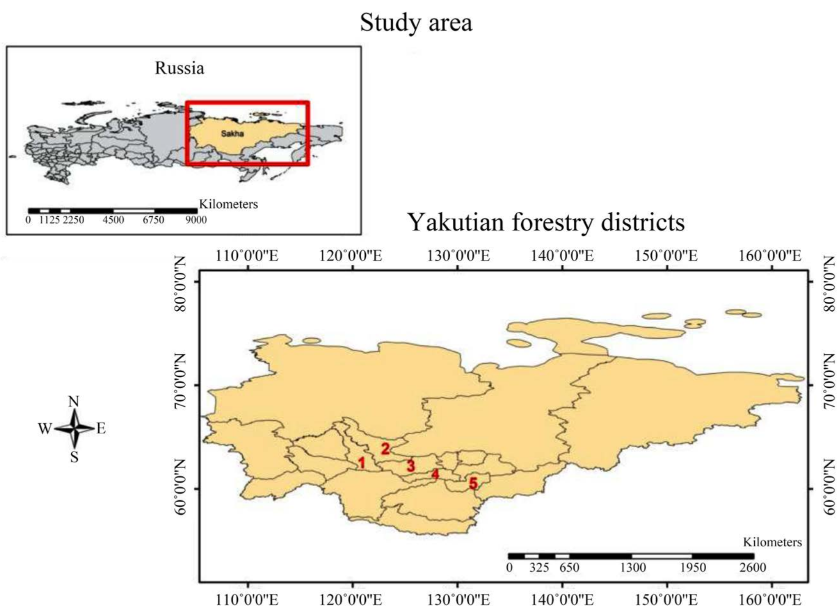


Figure 1. Extended study area map with borders of selected forestry districts, where 1—Verkhnevilyuisky (Verkhnevilyuisk), 2—Vilyuisky (Vilyuisk), 3—Gorny (Berdigestyakh), 4—Khangalassky (Pokrovsk), and 5—Amginsky (Amga) forestry districts.

Table 1. Characteristics of meteorological stations.

Station name/WMO Code	Forestry District	Latitude	Longitude
Amga/24962	Amginsky	131˚97'	60˚90'
Berdigestyakh/24758	Gorny	126˚70'	62˚10'
Pokrovsk/24856	Khangalassky	129˚14'	61˚48'
Verkhnevilyuisk/24644	Verkhnevilyuisky	120˚31'	63˚45'
Vilyuisk/24641	Vilyuisky	121˚63'	63˚75'

Data Source: All-Russia Research Institute of Hydrometeorological Information—World Data Center (RIHMI-WDC). List of the Russian Meteorological Stations (see URL in the References).

GIS data comprising files of the region boundaries has been downloaded from the website of the Russian Open GIS Portal "GIS-Lab" (see URL in the References).

2.3. Methodology

2.3.1. Research Design

We hypothesized that the recent extension of the fire season and related cumulative increases of the burned area in five forestry districts of the Sakha Republic were related to climate change as observable through two fundamental meteorological parameters, temperature and precipitation. We further hypothesized that the earlier coming of spring and later coming of fall, i.e. significant warming and drying trends during spring (April-May) and fall months (September-October) could be correlated to the increased fire activity.

To test hypotheses, we developed an approach to search for possible climate change signals in short-term fire weather ranks through widely used statistical techniques (see **Figure A1** in the **Appendix 2**).

We first collected data for the two most relevant climate phenomena, temperature and precipitation. A preliminary examination of the data for 1996-2018 showed four conspicuous trends in the recent period. We then constructed four indicators from these trends suggesting the existence of a climate change signal: 1) the magnitude of changes; 2) the pace of changes; 3) the inconsistency; and 4) significance of changes. For detection of climate change signals, all of the following conditions were respected:

1) the magnitude of changes has to be high;
2) the pace of changes has to be fast;
3) the changes have to be inconsistent;
4) detected changes have to be statistically significant.

The magnitude of changes we assessed by using differences from historical normals (for temperature) and differences from historical means (for precipitation). For the changes in pace, we analyzed it using the variability analysis including calculation of standard deviations, coefficients of variation, departures from historical normals (for temperature) and departures from historical means (for precipitation). Inconsistency was analyzed through analysis of homogeneity. The homogeneity analysis allowed us to find the timing of abrupt changes in the temporal evolution of selected meteorological parameters and direction of that changes, upward or downward. Finally, we employed the trend test to assess the significance of detected changes.

2.3.2. Methods

The search for detectable climate change signals in the short-term ranks of fire weather parameters was carried out in four steps (see **Figure A1** in **Appendix 2**). An initial descriptive statistical analysis was carried out in terms of comparison of recent fire weather means for 1996-2018 to historical normals (for 1961-1990 and 1989-2018) and calculation of their actual differences to see the magnitude of changes. The assessment of variability of the fire weather was held to find how fast and inconsistent were the changes. Homogeneity analysis was used to find the timing of abrupt changes and their consistency or otherwise around selected sites in the study area. Finally, we employed the trend test to assess the significance of detected trends.

For the first step, we computed basic descriptive statistics (means and standard deviations (SD)), historical normals for the most recent 30-year period, 1989-2018, and the reference WMO period, 1961-1990, for comparison. We prepared graphs of trends in fire weather parameters (temperature and precipitation) to visualize the changes (see **Appendix 3**). SDs were calculated for initial assessment of variability in the fire weather.

For the second step, we performed analysis of fire weather variability using coefficients of variation (CV), percentage departures from historical normals (for temperature, for the method see (WMO, 2017)), percentage departures from the mean (for atmospheric precipitation, for the method see (Kant, Meshram, & Sahu, 2014)) and precipitation concentration index (PCI, for the method see (Jaswal, Kumar, & Khare, 2014)).

The third step was devoted to the analysis of inconsistency and abrupt changes in the evolution of fire weather using homogeneity tests. Before the third step, an autocorrelation test was applied to the data series as the measure of lag-1 serial correlation. It was applied on the data to observe the presence of any significant correlation. Homogeneity was assessed by Pettitt's, Standard Normal Homogeneity's (SNHT) and Buishand's tests. Significance of detected trends was assessed by Mann-Kendall trend test as a final step of our analyses.

Data analyses were undertaken using MS Excel, XLSTAT Software, and MAKESENS Program for Trends Detection (Salmi et al., 2002).

3. Results and Discussion "Detecting Climate Change Signals in Fire Weather"

3.1. Recent Fire Weather Variability

In this study, we first used descriptive statistics to grasp monthly, annual, fire season and peak fire period characteristics and trends of main fire weather parameters such as air temperature and atmospheric precipitation. We computed historical normals for 1961-1990 and the most recent 30-year period, 1989-2018, for comparison with current means, 1996-2018 (Table 2 and Table 3). Descriptive statistics such as means and standard deviations were computed (Table 4 and Table 5). Also, we prepared graphs of temperature trends and precipitation trends during study period, 1996-2018, for each of the fire season month, annual, fire season and peak fire period for initial visual assessment of changes (see Figure A2 and Figure A3 in **Appendix 3**). Further identified trends were assessed for significance using the Mann-Kendall trend test.

Table 2. Historical normals for monthly, annual, seasonal and peak fire period means of temperature, in ˚C.

24962-Amga Meteorological Station, Amginsky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
1989-2018	−4.7	7.9	16.1	18.9	14.7	5.8	−7.9	−9.5	9.2	16.6
1961-1990	−6.8	6.5	14.6	17.7	13.8	5.1	−9.3	−11.0	8.1	15.4
24758-Berdigestyakh Meteorological Station, Gorny Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
1989-2018	−6.0	6.3	15.0	17.6	13.4	4.4	−8.1	−9.1	8.1	15.3
1961-1990	−7.5	5.2	13.5	16.3	12.5	3.9	−9.1	−10.6	7.1	14.1
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
1989-2018	−4.8	7.4	15.9	18.7	14.7	5.7	−7.2	−8.9	9.2	16.4
1961-1990	−6.3	6.3	14.5	17.8	14.1	5.3	−8.4	−10.1	8.3	15.5
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
1989-2018	−4.7	6.4	16.0	18.9	14.8	5.6	−6.9	−7.7	9.1	16.6
1961-1990	−7.0	5.2	14.5	18.1	14.1	5.2	−8.0	−9.2	8.2	15.5
24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
1989-2018	−5.4	6.1	15.3	18.1	14.0	5.2	−6.9	−8.1	8.6	15.8
1961-1990	−7.7	5.0	13.8	17.1	13.2	4.6	−7.9	−9.4	7.6	14.7

Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

Table 3. Historical means for the monthly, annual, seasonal and peak fire period total precipitation, in mm.

	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
24962-Amga Meteorological Station, Amginsky Forestry District										
1961-1990	7.6	19.0	36.5	42.1	50.1	31.5	18.7	21.4	33.0	42.9
1989-2018	8.2	21.3	39.2	50.6	55.8	39.4	27.7	24.2	39.0	48.5
24758-Berdigestyakh Meteorological Station, Gorny Forestry District										
1961-1990	10.1	19.3	38.5	42.8	36.2	28.9	25.1	21.0	31.8	39.2
1989-2018	10.2	27.0	34.1	44.0	51.4	38.4	24.1	24.0	36.5	43.2
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District										
1961-1990	9.1	19.7	40.0	42.8	39.7	30.1	18.4	20.8	31.8	40.8
1989-2018	14.2	23.8	32.5	53.2	44.3	32.8	24.5	22.9	35.2	43.3
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District										
1961-1990	11.4	18.9	33.2	46.1	37.3	27.2	23.9	21.2	31.1	38.9
1989-2018	10.8	27.6	33.8	49.1	41.1	32.4	26.2	23.8	35.0	41.3
24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District										
1961-1990	9.5	18.5	33.5	43.1	35.5	27.5	19.4	19.7	29.6	37.4
1989-2018	8.4	21.7	34.6	43.9	41.9	33.0	19.9	21.0	32.5	40.1

Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

Table 4. Basic descriptive statistics for the monthly, annual, seasonal and peak fire period means of temperature for the period 1996-2018 and their differences from historical normals (DFHN), in ˚C.

	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
24962-Amga Meteorological Station, Amginsky Forestry District										
Current mean	−4.4	8.1	16.2	19.1	15.0	5.8	−8.2	−9.4	9.3	16.8
SD	1.86	1.50	1.65	1.42	1.58	1.40	2.30	0.76	0.80	1.03
DFHN (1961-1990)	2.4	1.6	1.6	1.4	1.2	0.7	1.1	1.6	1.2	1.4
DFHN (1989-2018)	0.3	0.2	0.1	0.2	0.3	0.0	−0.3	0.1	0.1	0.2

Continued

24758-Berdigestyakh Meteorological Station, Gorny Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	−5.6	6.4	15.2	17.9	13.6	4.4	−8.6	−9.1	8.2	15.6
SD	2.78	1.61	1.59	1.49	1.48	1.36	2.42	0.90	0.84	1.05
DFHN (1961-1990)	1.9	1.2	1.7	1.6	1.1	0.5	0.5	1.5	1.1	1.5
DFHN (1989-2018)	0.4	0.1	0.2	0.3	0.2	0.0	−0.5	0.0	0.1	0.3
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	−4.3	7.4	16.1	19.0	14.9	5.6	−7.7	−8.8	9.2	16.6
SD	1.99	1.41	1.60	1.46	1.52	1.30	1.99	0.74	0.74	1.07
DFHN (1961-1990)	2.0	1.1	1.6	1.2	0.8	0.3	0.7	1.3	0.9	1.1
DFHN (1989-2018)	0.5	0.0	0.2	0.3	0.2	−0.1	−0.5	0.1	0.0	0.2
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	−4.1	6.6	16.4	19.2	14.8	5.7	−7.2	−7.6	9.2	16.8
SD	2.41	1.91	1.69	1.55	1.45	1.46	2.43	0.96	0.90	1.00
DFHN (1961-1990)	2.9	1.4	1.9	1.1	0.7	0.5	0.8	1.6	1.0	1.3
DFHN (1989-2018)	0.6	0.2	0.4	0.3	0.0	0.1	−0.3	0.1	0.1	0.2
24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	−4.8	6.2	15.6	18.3	14.1	5.3	−7.3	−8.0	8.7	16.0
SD	2.62	1.85	1.55	1.38	1.34	1.35	2.62	1.07	0.86	0.90
DFHN (1961-1990)	2.9	1.2	1.8	1.2	0.9	0.7	0.6	1.4	1.1	1.3
DFHN (1989-2018)	0.6	0.1	0.3	0.2	0.1	0.1	−0.4	0.1	0.1	0.2

Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

Table 5. Basic descriptive statistics for the monthly, annual, seasonal and peak fire period means of total precipitation for the period 1996-2018 and their differences from historical means (DFHM), in mm.

24962-Amga Meteorological Station, Amginsky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	9.9	23.5	42.5	50.0	61.2	42.3	31.7	25.8	41.9	51.2
SD	9.1	16.9	29.8	34.7	40.9	22.6	31.8	6.7	12.9	20.1
DFHM (1961-1990)	2.3	4.5	6.0	7.9	11.1	10.8	13.0	4.4	8.9	8.3
DFHM (1989-2018)	1.7	2.2	3.3	-0.6	5.4	2.9	4.0	1.6	2.9	2.7
24758-Berdigestyakh Meteorological Station, Gorny Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	10.8	26.2	33.5	45.1	59.3	40.8	23.5	25.0	38.1	46.0
SD	6.3	27.6	19.1	27.5	37.4	23.2	12.8	5.6	10.6	17.5
DFHM (1961-1990)	0.7	6.9	−5.0	2.3	23.1	11.9	−1.6	4.0	6.3	6.8
DFHM (1989-2018)	0.6	−0.8	−0.6	1.1	7.9	2.4	−0.6	1.0	1.6	2.8
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	17.1	22.7	28.1	55.6	48.6	35.0	26.6	23.7	36.1	44.1
SD	29.6	14.8	21.2	38.9	29.3	24.3	27.9	7.9	12.0	17.6
DFHM (1961-1990)	8.0	3.0	−11.9	12.8	8.9	4.9	8.2	2.9	4.3	3.3
DFHM (1989-2018)	2.9	−1.1	−4.4	2.4	4.3	2.2	2.1	0.8	0.9	0.8
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	11.2	31.0	33.9	50.5	44.9	34.0	24.4	24.5	36.5	43.1
SD	7.6	25.6	17.6	28.6	23.9	19.5	11.5	4.6	8.4	12.8
DFHM (1961-1990)	−0.2	12.1	0.7	4.4	7.6	6.8	0.5	3.3	5.4	4.2
DFHM (1989-2018)	0.4	3.4	0.1	1.4	3.8	1.6	−1.8	0.7	1.5	1.8

Continued

24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
Current mean	8.5	23.2	35.1	46.5	45.1	34.5	18.6	21.7	33.8	42.2
SD	5.3	16.7	18.2	26.9	22.4	22.2	7.0	4.1	8.2	10.6
DFHM (1961-1990)	−1.0	4.7	1.6	3.4	9.6	7.0	−0.8	2.0	4.2	4.8
DFHM (1989-2018)	0.1	1.5	0.5	2.6	3.2	1.5	−1.3	0.7	1.3	2.1

Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

Table 2 and Table 4 show that temperature is increasing throughout the year in all stations, especially in April which is now the onset month of the fire season in the Sakha Republic. The temperature increases in April and October has been shown to correlate with the extension of the fire season itself; it also makes the fire activity more intense and increases the extent of the burned area due to cumulative increase of burned area from early spring and throughout the entire fire season (see Kirillina, Shvetsov, Protopopova, Thiesmeyer, & Yan, 2020). Similarly, the results of our previous research reporting about the earlier beginnings of the fire season in April and cumulative increase of burned area in the Sakha Republic strongly support this finding. We found a substantial increase of temperature up to 1.9˚C in the onset month of the peak fire period, June, too. Also, a significant increasing trend was found in the peak fire month July ((the month with the highest extent of burned area) as shown in the article mentioned above)) as high as up to 1.6˚C, which as we have seen intensifies the fire weather itself and fire activity. Identified increases in the monthly means in turn increased the annual, seasonal and peak fire temperatures.

The onset (April-May) and the ending (October) months of the fire season showed the highest variability in temperature indicated by high values of SD. This might be a signal of climate change, because temperatures in these months were not just significantly increased, but were highly dispersed, inconsistent and changed very fast, as shown in Table 6.

In turn, precipitation changes are inconsistent and differ from station to station. However, in some stations we found significant decreases of precipitation at the beginning of the peak fire period in June. The highest inconsistency and dispersion in precipitation illustrated by high SDs were shown during peak fire period and the ending month of the fire season in October.

As the second step, we performed analysis of fire weather variability using coefficients of variation, percentage departures from historical normals (for temperature), percentage departures from the mean (for precipitation) and precipitation concentration index to identify possible changes in temperature and precipitation patterns (Table 6 and Table 7).

Table 6. Variability analysis for temperature, 1996-2018.

	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
24962-Amga Meteorological Station, Amginsky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	42.69	18.48	10.19	7.41	10.55	24.17	28.02	8.14	8.62	6.15
Percentage departure from historical normal (1961-1990)	35.9	25.1	10.8	8.2	8.7	14.0	11.5	14.7	15.3	8.9
Percentage departure from historical normal (1989-2018)	7.2	2.9	0.5	1.8	1.3	2.0	-2.8	1.2	1.5	1.7
24758-Berdigestyakh Meteorological Station, Gorny Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	49.81	24.95	10.46	8.34	10.86	31.09	9.94	10.21	10.26	6.72
Percentage departure from historical normal (1961-1990)	25.5	24.0	12.4	9.5	9.0	12.0	5.9	14.3	14.8	10.3
Percentage departure from historical normal (1989-2018)	5.3	2.3	1.2	1.5	0.9	1.6	3.2	0.4	0.6	1.7
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	46.51	18.95	9.99	7.65	10.24	23.06	25.83	8.43	8.02	6.40
Percentage departure from historical normal (1961-1990)	32.4	−0.9	7.6	3.0	0.2	−0.9	13.4	12.7	11.3	7.3
Percentage departure from historical normal (1989-2018)	11.2	−14.5	−1.2	−2.0	−4.6	−6.2	0.4	0.4	1.4	1.0

Continued

24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	59.21	28.96	10.34	8.08	9.77	25.73	33.89	12.56	9.74	5.95
Percentage departure from historical normal (1961-1990)	41.9	26.9	13.0	6.0	5.1	8.8	10.2	16.9	12.7	8.3
Percentage departure from historical normal (1989-2018)	13.5	3.1	2.4	1.5	0.1	1.0	−4.1	0.7	1.6	1.2
24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	54.34	29.59	9.95	7.51	9.46	25.76	36.03	13.31	9.86	5.64
Percentage departure from historical normal (1961-1990)	37.3	24.9	13.1	7.2	7.0	14.2	7.9	14.4	14.7	9.0
Percentage departure from historical normal (1989-2018)	10.5	2.4	2.0	1.3	0.2	1.0	−3.9	0.7	1.3	1.4

Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

Table 7. Variability analysis for precipitation, 1996-2018.

24962-Amga Meteorological Station, Amginsky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	91.7	72.2	70.3	69.3	66.8	53.5	100.2	25.9	30.9	39.2
Percentage departure from the mean (1961-90)	30.7	23.5	16.3	18.9	22.2	34.1	69.7	20.7	26.9	19.4
Percentage departure from the mean (1989-2018)	21.2	10.2	8.3	−1.1	9.7	7.2	14.6	6.7	7.3	5.7
PCI	3.2	7.6	13.7	16.2	19.8	13.7	10.3	–	-	-

Continued

	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
24758-Berdigestyakh Meteorological Station, Gorny Forestry District										
CV	58.4	105.5	57.1	61.1	63.0	56.8	54.3	22.4	27.9	38.1
Percentage departure from the mean (1961-90)	6.8	35.8	−13.0	5.3	63.9	41.0	−6.3	18.9	19.7	17.3
Percentage departure from the mean (1989-2018)	5.7	−2.9	−1.7	2.4	15.4	6.1	−2.4	4.0	4.3	6.4
PCI	3.6	8.8	11.2	15.0	19.8	13.6	7.9	-	-	-
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	172.5	65.3	75.7	70.0	60.3	69.4	104.7	33.3	33.1	39.8
Percentage departure from the mean (1961-90)	88.3	15.0	−29.8	29.9	22.3	16.4	44.8	13.7	13.5	8.0
Percentage departure from the mean (1989-2018)	20.7	−4.8	−13.6	4.5	9.6	6.8	8.7	3.3	2.5	1.8
PCI	6.0	8.0	9.9	19.6	17.1	12.3	9.4	-	-	-
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	68.2	82.6	52.0	56.6	53.2	57.3	47.0	18.6	23.0	29.7
Percentage departure from the mean (1961-90)	−1.7	63.8	2.1	9.6	20.5	25.1	2.3	17.2	17.2	10.8
Percentage departure from the mean (1989-2018)	3.8	12.1	0.3	2.9	9.3	5.0	−6.7	3.1	4.2	4.4
PCI	3.8	10.5	11.5	17.2	15.3	11.6	8.3	-	-	-

Continued

24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District										
	April	May	June	July	August	September	October	Annual	Fire season	Peak fire period
CV	62.2	72.1	52.0	57.9	49.6	64.4	37.5	18.8	24.3	25.0
Percentage departure from the mean (1961-90)	−10.4	25.5	4.6	7.9	27.0	25.6	−4.2	10.2	14.3	12.9
Percentage departure from the mean (1989-2018)	1.3	7.0	1.3	5.9	7.6	4.6	−6.6	3.4	4.1	5.3
PCI	3.3	8.9	13.5	17.9	17.3	13.3	7.1	-	-	-

Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

As mentioned above, considerable variation of temperature was observed at the beginning (April-May) and at the end of the fire season (September-October), ranging as high as up to 59% at the onset of the fire season in April and up to 36% at the end of the season. This again clearly indicates significant changes of temperature at the onset and the ending months of the fire season as it was found earlier.

Table 6 also reports that the highest departures in temperature again were exhibited at the beginning (April and May) and at the end of the fire season (September-October).

This indication of continuing significant changes of temperature at the onset and ending months of the fire season is often correlated to more intense fire activity (as mentioned above), but the above comparison of the historical normals with the current study period showed definable periods of change, which provided an important step toward identifying detectable climate change signals.

Precipitation shows considerable variation throughout the year with the highest values of CV at the beginning (April-May) and at the end of the season (September-October).

Similarly, the highest departures from historical means were also found at the beginning and end of the fire season.

Also, we detected negative departures in some stations at the beginning of the peak fire period in June, which might intensify a drought situation and make the fire season more severe. One station (24856-Pokrovsk, Khangalassky forestry district) showed moderate drought conditions in June (with the percentage departure from historical mean −29.8%).

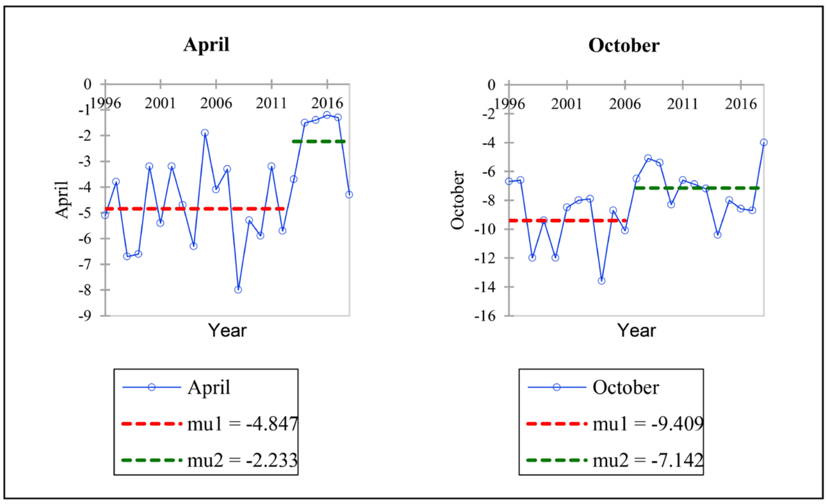
The highest PCI in the current period was detected in July and August in all five districts; though the monthly precipitation distribution in July and August months is irregular, cumulative precipitation is higher these two months. If there is precipitation decrease in any months it may severely affect the fire season and intensify fire activity, especially if it is accompanied by significant increases in temperature as may be happening in Berdigestyakh and Pokrovsk. The significance of these two as potential climate change signals is discussed below.

3.2. Inconsistency and Abrupt Changes in the Evolution of Fire Weather

For the analysis of inconsistency and abrupt changes in the evolution of fire weather we applied homogeneity tests in order to detect significant inhomogeneity that could signal change points. Prior to the analysis of homogeneity, we applied an autocorrelation test. None of the temperature data series show significant autocorrelation. The same results were found for precipitation. Then we assessed the homogeneity of the weather data series using the Pettitt's, SNHT's and Buishand's tests in order to detect specific change points towards prolonged trends, and their directions—upward or downward (see Table 8 and Table 9, Figures 2-26).

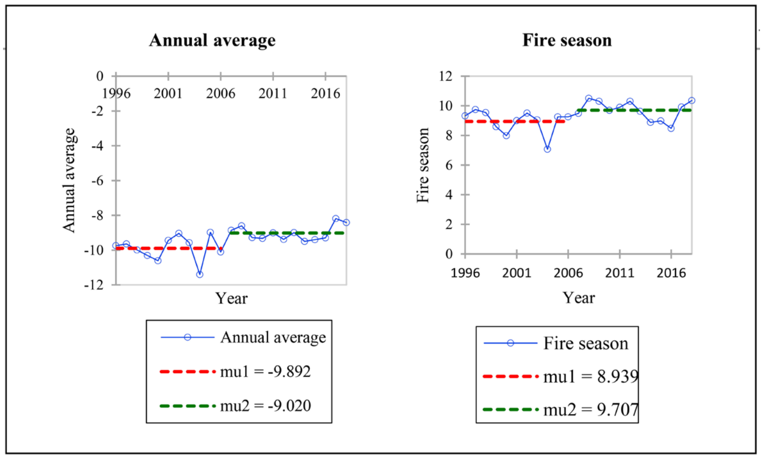
Figures 2-14 and Table 8 show several possible change points for temperature which occurred abruptly, and were also shown by variability analyses.

Results for the homogeneity tests for temperature show statistically significant inhomogeneity at the beginning (April-May) and at the end of the fire season (September-October), and also inhomogeneity at the annual and seasonal scales (see Table 8). In the five districts, significant shifts in temperature during the fire season and at the annual scale occurred in 2006. In these districts the change point can plausibly be 2006.



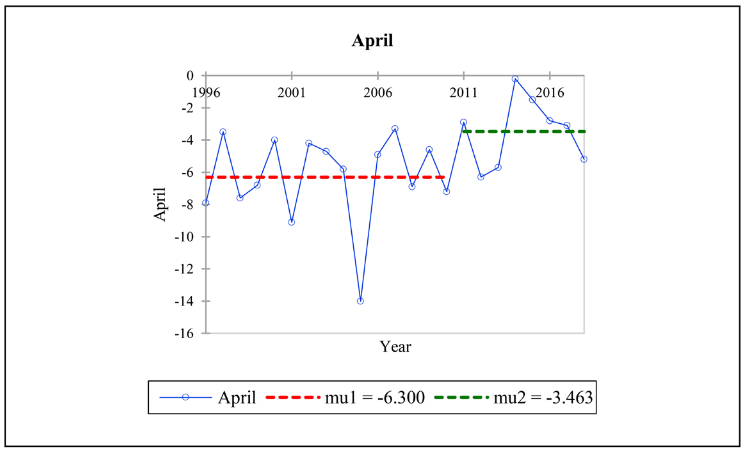
24962-Amga Meteorological Station, Amginsky Forestry District.

Figure 2. Months with significant change points for upward shifts in the temperature, for 1996-2018 in April and October.



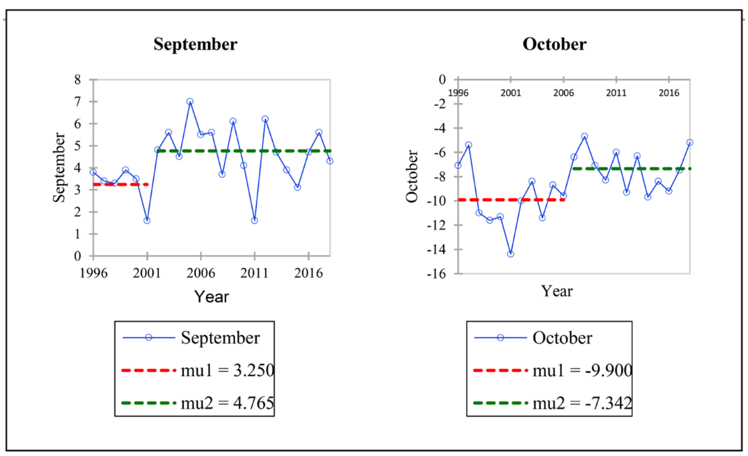
24962-Amga Meteorological Station, Amginsky Forestry District.

Figure 3. Annual and seasonal upward shifts in the temperature, for 1996-2018.



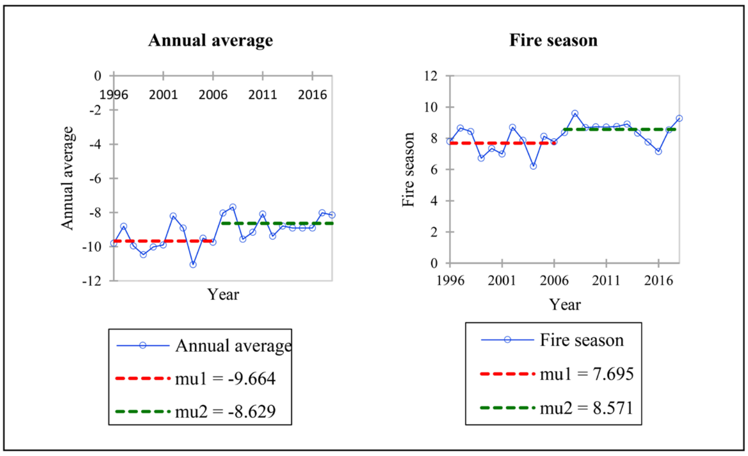
24758-Berdigestyakh Meteorological Station, Gorny Forestry District.

Figure 4. Month with significant change points for upward shifts in the temperature, for 1996-2018 in April.



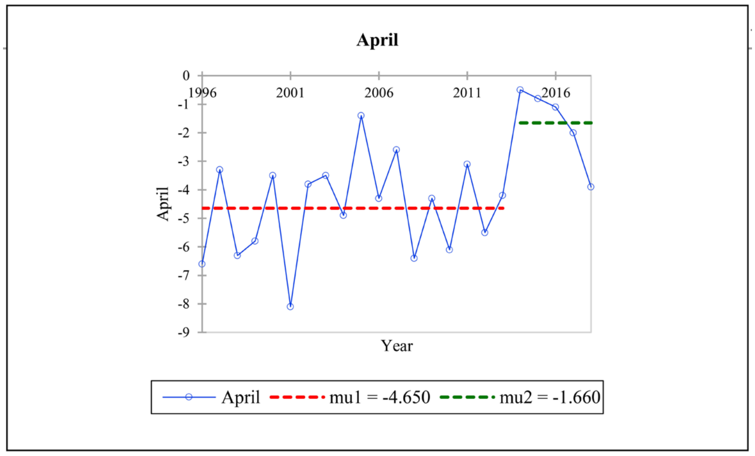
24758-Berdigestyakh Meteorological Station, Gorny Forestry District.

Figure 5. Months with significant change points for upward shifts in the temperature, for 1996-2018 in September and October.



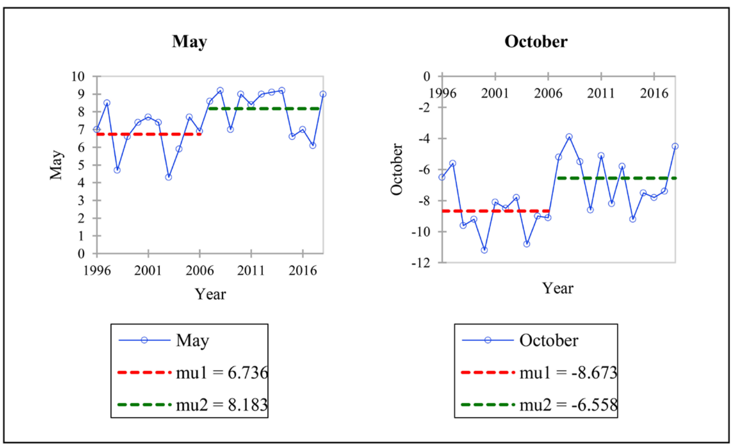
24758-Berdigestyakh Meteorological Station, Gorny Forestry District.

Figure 6. Annual and seasonal upward shifts in the temperature, for 1996-2018.



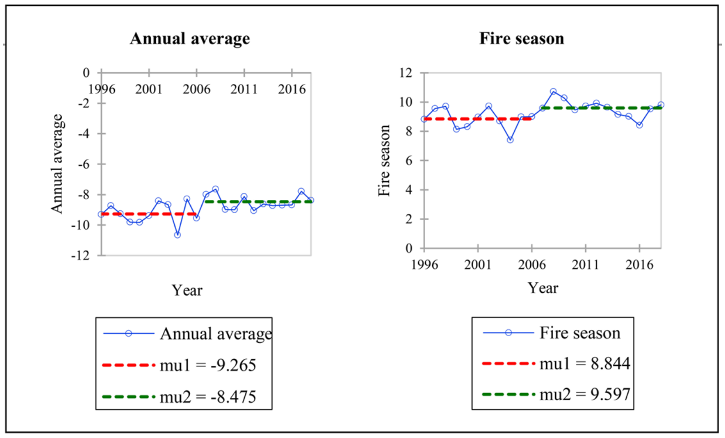
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District.

Figure 7. Month with significant change points for upward shifts in the temperature, for 1996-2018 in April.



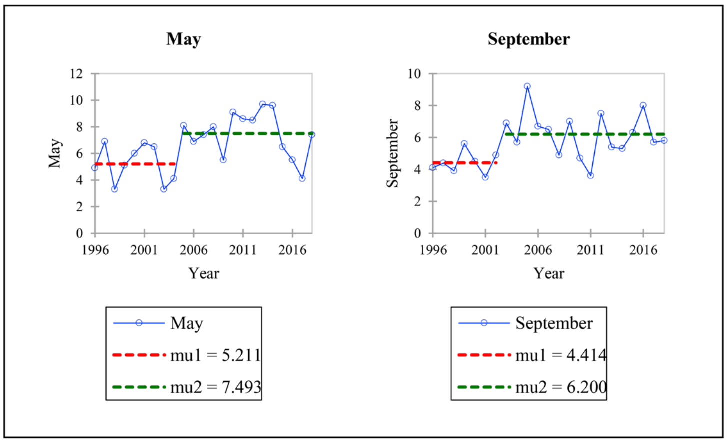
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District.

Figure 8. Months with significant change points for upward shifts in the temperature, for 1996-2018 in May and October.



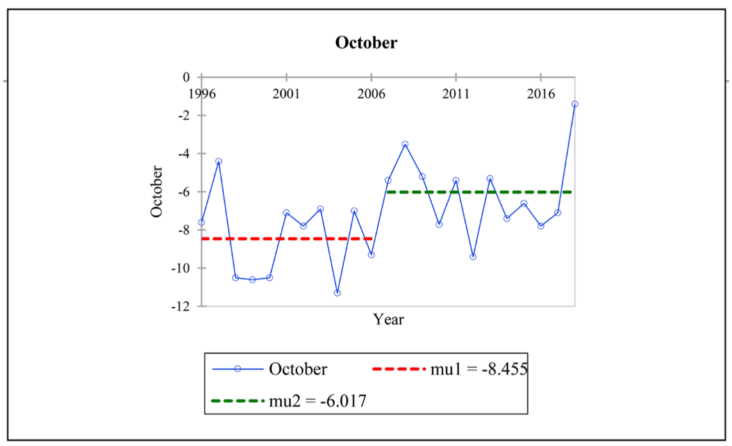
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District.

Figure 9. Annual and seasonal upward shifts in the temperature, for 1996-2018.



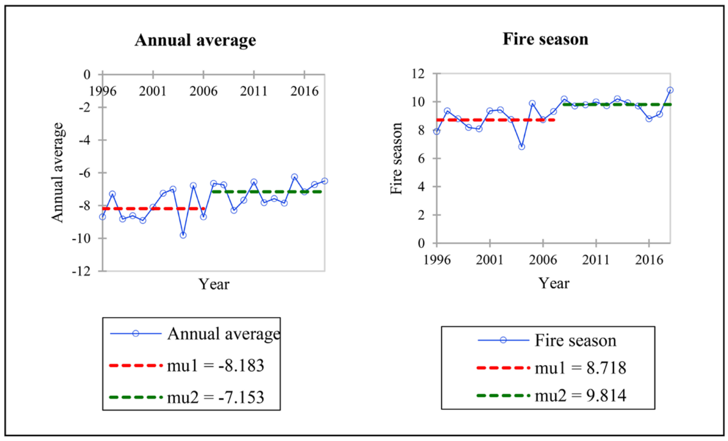
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District.

Figure 10. Months with significant change points for upward shifts in the temperature, for 1996-2018 in May and September.



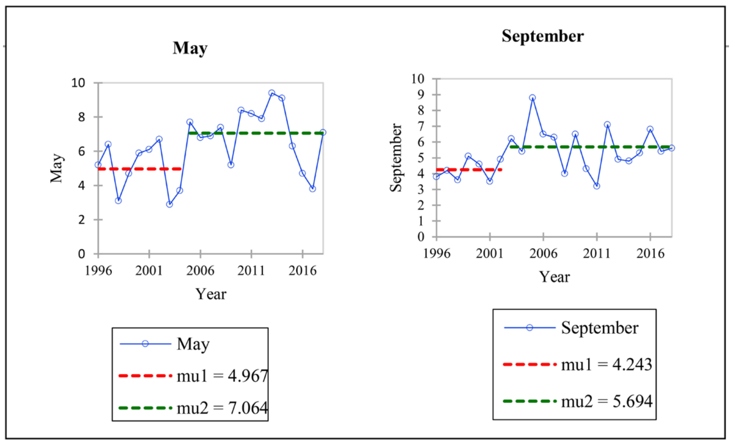
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District.

Figure 11. Month with significant change points for upward shifts in the temperature, for 1996-2018 in October.



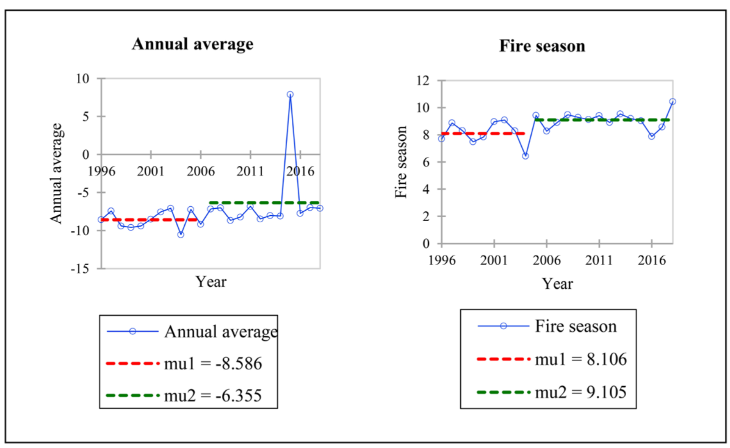
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District.

Figure 12. Annual and seasonal upward shifts in the temperature, for 1996-2018.



24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District.

Figure 13. Months with significant change points for upward shifts in the temperature, for 1996-2018 in May and September.



24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District.

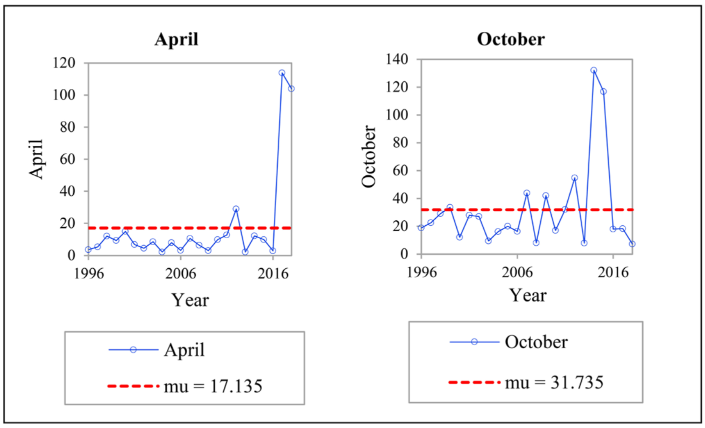
Figure 14. Annual and seasonal upward shifts in the temperature, for 1996-2018.

Table 8. The results of homogeneity tests for temperature.

24962-Amga Meteorological Station, Amginsky Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
April	0.023	2012	0.016	2012	0.016	2012
October	0.045	2006	"-"	"-"	0.025	2006
Annual average	0.001	2006	0.031	2006	0.001	2006
Fire season	0.043	2006	"-"	"-"	0.034	2006
24758-Berdigestyakh Meteorological Station, Gorny Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
April	0.027	2010	"-"	"-"	0.042	2010
September	0.033	2001	"-"	"-"	"-"	"-"
October	0.015	2006	"-"	"-"	0.014	2006
Annual average	0.003	2006	0.013	2006	0.003	2006
Fire season	0.014	2006	"-"	"-"	0.017	2006
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
April	0.040	2013	0.017	2013	0.025	2013
May	0.025	2006	"-"	"-"	0.021	2006
October	0.014	2006	"-"	"-"	0.017	2006
Annual average	0.008	2006	0.040	2006	0.005	2006
Fire season	0.019	2006	"-"	"-"	0.019	2006
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
May	0.007	2004	0.030	2004	0.010	2004
September	0.007	2002	0.049	2002	0.016	2002
October	0.042	2006	"-"	"-"	0.022	2006
Annual average	0.012	2006	"-"	"-"	0.016	2006
Fire season	0.001	2004	0.016	2004	0.002	2004
24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
May	0.008	2004	0.049	2004	0.014	2004
September	0.033	2002	"-"	"-"	0.043	2002
October	"-"	"-"	"-"	"-"	0.042	2006
Annual average	0.029	2006	"-"	"-"	0.032	2006
Fire season	0.007	2004	"-"	"-"	0.008	2004

"-" Inhomogeneity was not detected. Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

Next we show the results of homogeneity tests for precipitation (Table 9 and Figures 15-26).



24962-Amga Meteorological Station, Amginsky Forestry District.

Figure 15. Monthly shifts in precipitation, for 1996-2018 in May and October (inhomogeneity was not found).

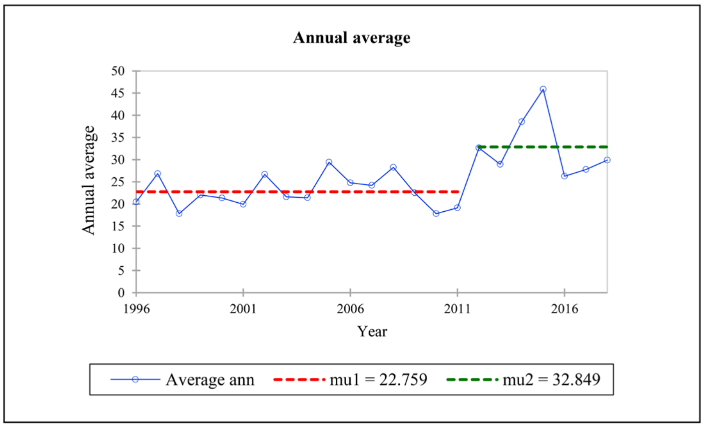
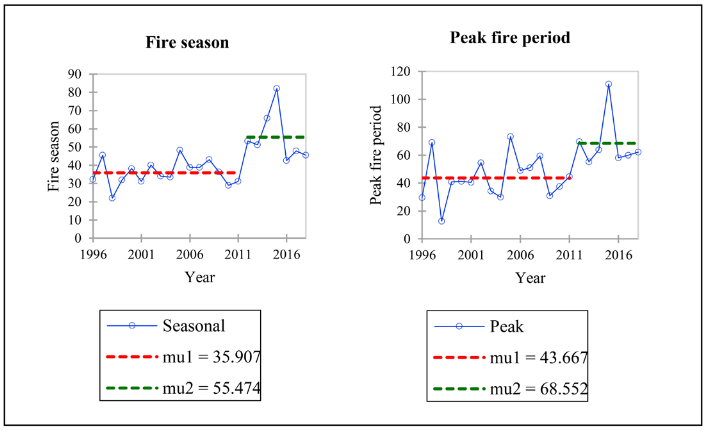
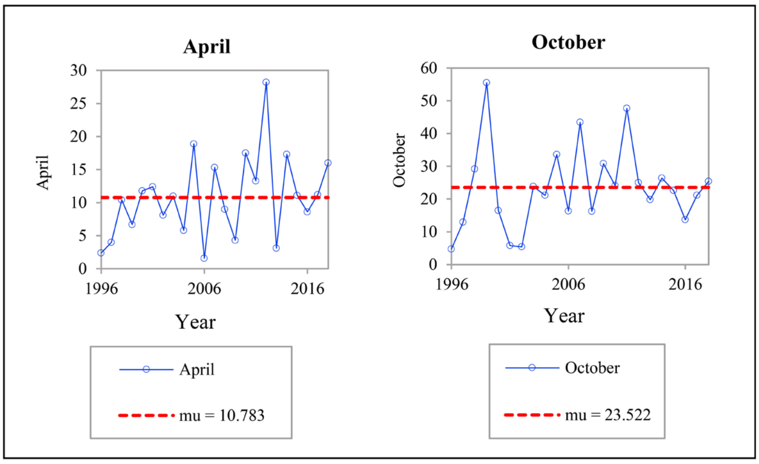


Figure 16. Annual shifts in precipitation, for 1996-2018.



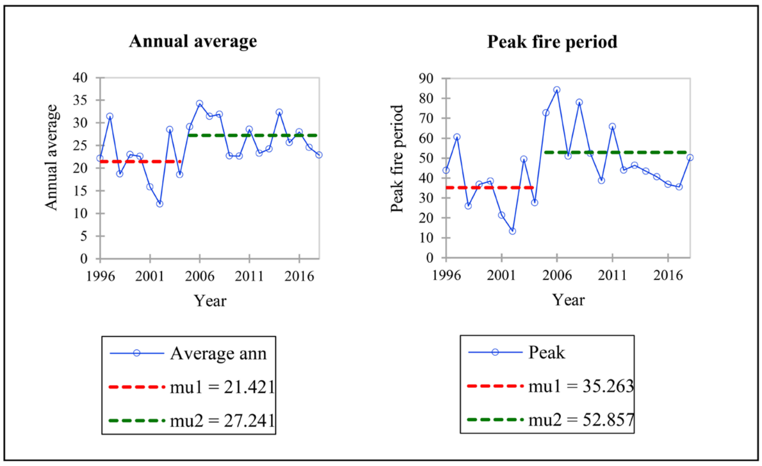
24962-Amga Meteorological Station, Amginsky Forestry District.

Figure 17. Seasonal and peak fire period shifts in precipitation, for 1996-2018.



24758-Berdigestyakh Meteorological Station, Gorny Forestry District.

Figure 18. Monthly shifts in precipitation, for 1996-2018 in April and October (inhomogeneity was not found).



24758-Berdigestyakh Meteorological Station, Gorny Forestry District.

Figure 19. Annual and peak fire period shifts in precipitation, for 1996-2018.

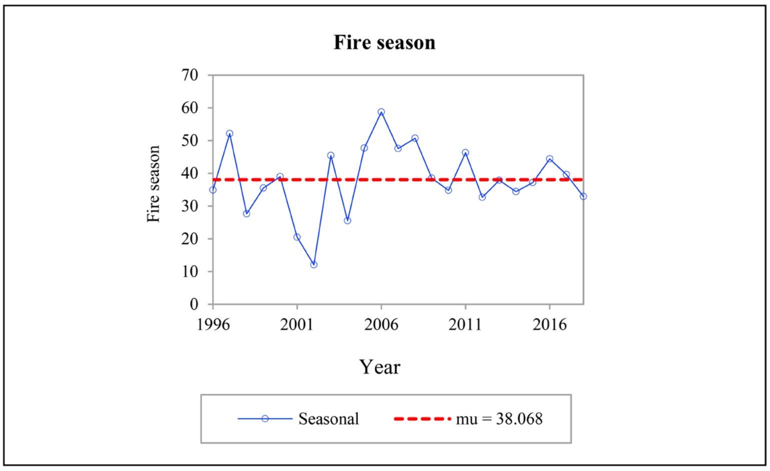
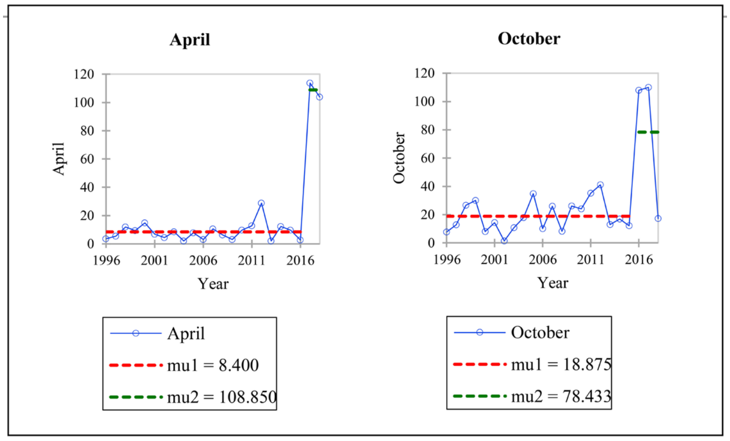
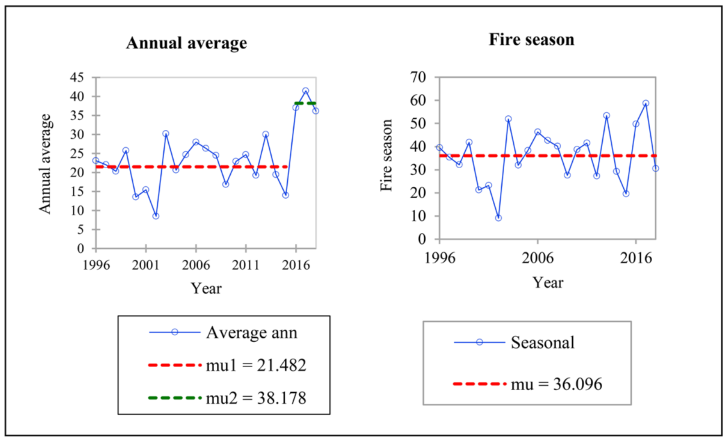


Figure 20. Seasonal shifts in precipitation, for 1996-2018 (inhomogeneity was not found).



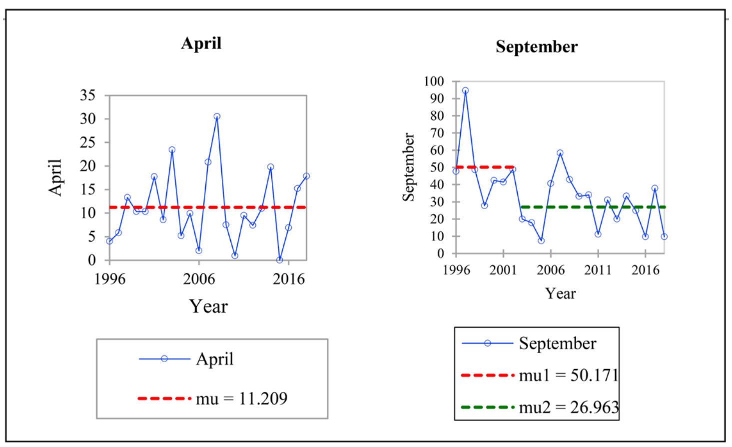
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District.

Figure 21. Monthly shifts in precipitation, for 1996-2018 in April and October.



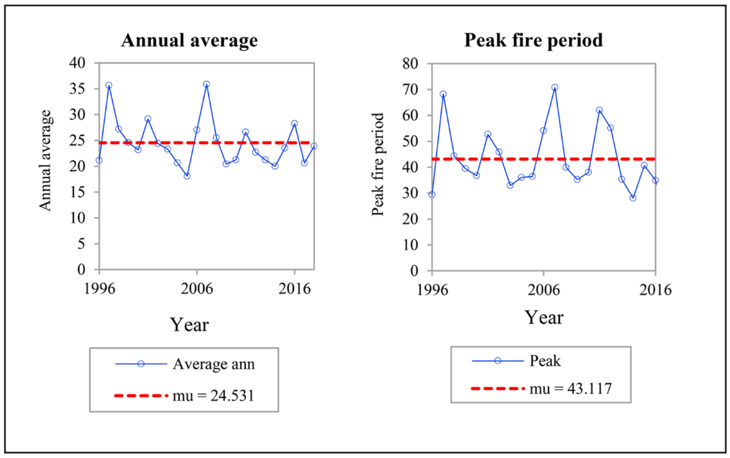
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District.

Figure 22. Annual and seasonal shifts in precipitation, for 1996-2018 (seasonal shift was not found).



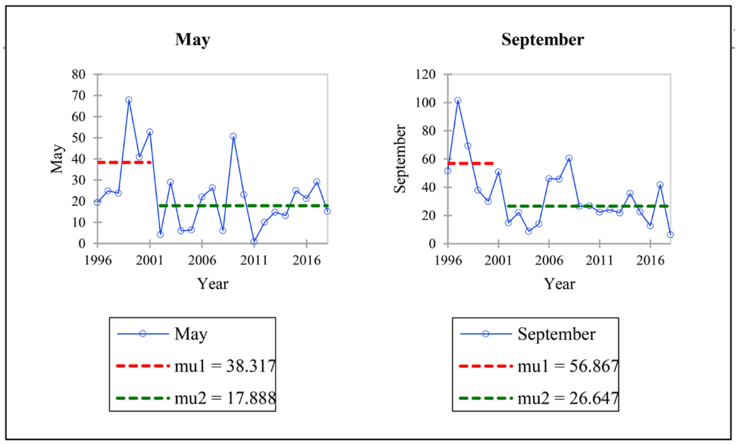
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District.

Figure 23. Monthly shifts in precipitation, for 1996-2018 in April and September (shift in April was not found).



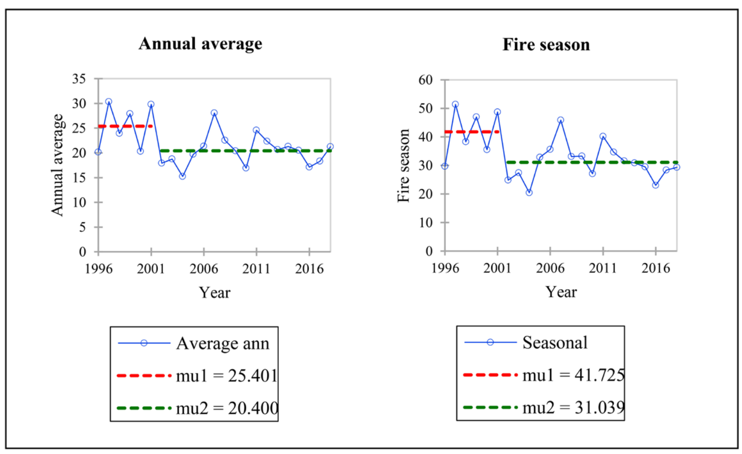
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District.

Figure 24. Annual and peak fire period shifts in precipitation, for 1996-2018 (inhomogeneity was not found).



24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District.

Figure 25. Monthly shifts in precipitation, for 1996-2018 in May and September.



24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District.

Figure 26. Annual and seasonal shifts in precipitation, for 1996-2018.

Table 9. The results of the homogeneity tests for precipitation.

24962-Amga Meteorological Station, Amginsky Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
			Increase			
Annual average	0.003	2011	0.011	2011	0.000	2011
			Increase			
Fire season	0.002	2011	0.012	2011	0.012	2011
			Increase			
Peak fire period	0.013	2011	"-"	"-"	0.011	2011
24758-Berdigestyakh Meteorological Station, Gorny Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
			Increase			
Annual average	0.017	2004	"-"	"-"	0.027	2004
			Increase			
Peak fire period	0.032	2004	"-"	"-"	0.031	2004
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
			Increase			
April	"-"	"-"	0.004	2016	0.004	2016
			Increase			
October	"-"	"-"	0.017	2015	0.026	2015
			Increase			
Annual average	"-"	"-"	0.001	2015	0.030	2015
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
			Decrease			
September	0.018	2002	"-"	"-"	0.016	2002
24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District						
Variable	*P test (Pettitt)*	*Change point*	*P test (SNHT)*	*Change point*	*P test (Buishand)*	*Change point*
			Decrease			
May	"-"	"-"	"-"	"-"	0.033	2001
			Decrease			
September	0.020	2001	0.010	2001	0.013	2001
			Decrease			
Annual average	"-"	"-"	"-"	"-"	0.041	2001
			Decrease			
Fire season	0.036	2001	0.044	2001	0.025	2001

"-"Inhomogeneity was not detected. Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

The results of the homogeneity test for precipitation show downward shifts at the beginning (April-May) and the end of the fire season (September-October) as well as in the annual scale for Vilyuisk and Verkhnevilyuisk. Three stations in Central Yakutia (Amga, Berdigestyakh and Pokrovsk) show upward shifts in annual and peak fire precipitation. One station (Pokrovsk) shows upward shifts at the beginning (April) and at the end of the fire season (October).

Although drying trends are not totally synchronous with warming trends, they do show some correlation to the burned area, as shown in the list of districts burned area below. Precipitation shows a general decrease in two stations (Vilyuisk and Verkhnevilyuisk). Precipitation shows an area-wide decrease in all five stations in the specific years 2001-2002 (Amga-2001, Berdigestyakh-2001 and 2002, Pokrovsk-2001). The years with downward shifts in precipitation (2001 and 2002) were the years with most burned area during the 2000s in all forestry districts (burned area data compiled by coauthor Shvetsov, E.G., 10.24.2019, available from Shvetsov, E.G. in English, by email). It seems to be a change signal less significant than temperature during the selected study period but should be worth further examination with longer-period and more location specific data.

The data for burned area for 2001 and 2002 fire seasons are presented below:

- Amga, Amginsky forestry district—with cumulative burned area 8.1 × 1000 ha—in 2001 and 14.7 × 1000 ha—in 2002 (with average for 2000-2009 10.8 ± 6.16 (standard error—SE) × 1000 ha).
- Berdigestyakh, Gorny forestry district—with cumulative burned area 182.1 × 1000 ha—in 2001 and 1227.1 × 1000 ha—in 2002 (with average for 2000-2009 146.3 ± 121.38 (SE) × 1000 ha).
- Pokrovsk, Khangalassky forestry district—with cumulative burned area 29.7 × 1000 ha—in 2001 and 621.1 × 1000 ha—in 2002 (with average for 2000-2009 66.7 ± 61.67 (SE) × 1000 ha).
- Vilyuisk, Vilyuisky forestry district—with cumulative burned area 88.2 × 1000 ha—in 2001 and 473.0 × 1000 ha—in 2002 (with average for 2000-2009 73.1 ± 45.98 (SE) × 1000 ha).
- Verkhnevilyuisk, Verkhnevilyuisky forestry district—with cumulative burned area 56.8 × 1000 ha—in 2001 and 172.1 × 1000 ha—in 2002 (with average for 2000-2009 26.4 ± 17.10 (SE) × 1000 ha).

However, these are not the years with much of the high temperature shifts.

The spatial inconsistency in precipitation trends, and their occasional lack of correlation to temperature trends, will need to be explained in further research incorporating more variables such as evapotranspiration and other mitigating factors.

3.3. Trends in Fire Weather

In order to identify the significance of detected trends and calculate the magnitude of trends in the fire weather, we performed the Mann-Kendall's trend test and the Sen's slope estimation (**Table 10** and **Table 11**).

Table 10. Mann-Kendall test results for temperature, 1996-2018.

	Test Z statistic	Q, Sen's slope estimate	Significance
24962-Amga Meteorological Station, Amginsky Forestry District			
Annual average	3.06	0.066	0.01
24758-Berdigestyakh Meteorological Station, Gorny Forestry District			
October	1.74	0.141	0.10
Annual average	2.72	0.076	0.01
Fire season	1.80	0.049	0.10
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District			
Annual average	2.40	0.053	0.05
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District			
May	2.06	0.167	0.05
June	2.04	0.100	0.05
September	2.06	0.089	0.05
Annual	2.85	0.075	0.01
Season	2.72	0.072	0.01
24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District			
April	2.26	0.076	0.05
May	2.06	0.150	0.05
June	1.80	0.085	0.10
September	1.88	0.076	0.10
Annual average	2.26	0.076	0.05
Peak fire period	2.22	0.058	0.05

Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

Table 11. Mann-Kendall test results for precipitation, 1996-2018.

	Test Z statistic	Q, Sen's slope estimate	Significance
24962-Amga Meteorological Station, Amginsky Forestry District			
July	3.09	3.013	0.01
Annual average	2.59	0.464	0.01
Fire season	2.59	0.850	0.01
24758-Berdigestyakh Meteorological Station, Gorny Forestry District			
April	1.74	0.333	0.10
September	−1.74	−1.000	0.10
24856-Pokrovsk Meteorological Station, Khangalassky Forestry District			
September	−1.77	−1.064	0.10
October	2.06	0.863	0.05
24641-Vilyuisk Meteorological Station, Vilyuisky Forestry District			
September	−2.67	−1.292	0.01
24644-Verkhnevilyuisk Meteorological Station, Verkhnevilyuisky Forestry District			
September	−2.43	−1.457	0.05
Fire season	−2.11	−0.512	0.05

Data Source: generated from NOAA GSOD dataset (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd).

These tests confirmed that temperatures showed significant increases in the onset (April-May) and in the ending months of the fire season (September-October). Also, significant upward trends were found for annual and seasonal scales and during the peak fire period, which can be used in formulating a climate signal.

With regard to precipitation, we found some significant upward and downward trends. Upward trends in precipitation were found at the annual and seasonal scales. Significant downwards trends were detected at the end of the fire season in September in two districts. The previous step of analysis, the homogeneity tests, showed the time of the most significant decrease in the study period, 2001-2002, which were years of greater burned area. Decreasing precipitation trends in September indicate a recent rainfall shortage (regarding Solovyev (Solovyev & Kozlov, 2005); historically, heavy rainfalls in August and September closed the fire season), which now extend the fire season, and in turn may increase cumulative extent of burned area.

4. Conclusion

In this paper, taking the Republic of Sakha (Yakutia) of Russia as the study area, we aimed to develop an approach for detecting signals indicating changes in fire weather due to climate change, in order to express recent fire weather variability, relating it to fire variability by using short-term ranks of the major meteorological parameters of air temperature and atmospheric precipitation.

In our previous published study, we had also found evidence in temperature trends of their correlation to an extension of the duration of the fire season and significant increase of burned area extent (Kirillina, Shvetsov, Protopopova, Thiesmeyer, & Yan, 2020). The results of this current research show the possibility of finding climate change signals that can be related to changes in recent fire weather, illustrated by the following findings:

1) The initial descriptive analysis found that temperature was increasing throughout the year in all stations, especially in the onset month of the fire season, April, and at the beginning of the peak fire period in June. In two stations (Berdigestyakh and Pokrovsk) we also detected notable decreases in precipitation at the beginning of the peak fire period in June and annual decreases during 2001-2002 in all.

Both temperature and precipitation showed high inconsistency and dispersion illustrated by high SDs. However, temperature showed the highest variability at the onset (April-May) and the ending (October) months of the fire season. The highest inconsistency and dispersion in precipitation for the current period were found during peak fire period and at the end of the fire season (September-October). Both changes testify to rapid changes and inconsistencies in the selected weather ranks, which might prove useful as signals of climate change when further consistency can be established.

2) The variability analysis also shows considerable variation of temperature again at the beginning (April-May) and at the end of the fire season (Septem-

ber-October), ranging as high as up to 59% at the onset of the fire season in April and up to 36% at the end of the season. In regard to precipitation, it shows the highest values of CV at the beginning of the fire season (April-May) and at the end of the season (September-October). The high CVs give indication of fast changes in both temperature and precipitation, which can be early signals of climate change. In regard to temperature, positive departures from historical normals can signal about warming trends. For precipitation, negative departures from the means can signal about rainfall shortage, which will be discussed below in finding 4.

The highest departures in temperature again were exhibited at the beginning (April and May) and at the end of the fire season (September-October) for all five districts. The highest departures from historical means for precipitation were found at the beginning and end of the fire season for all five districts. Also, we detected negative departures in two stations (Berdigestyakh and Pokrovsk) at the beginning of the peak fire period in June, which might intensify the drought situation and make the fire season more severe. One station (24856-Pokrovsk, Khangalassky forestry district) showed moderate drought conditions in June (with the percentage departure from historical normal −29.8%).

3) Homogeneity analysis results for temperature consistent with results of two previous steps. Significant inhomogeneity in temperature ranks was found again at the beginning of the fire season (April-May) and at the end of the season (September-October), and we also found inhomogeneity at the annual and seasonal scales. Significant upward shifts in temperature during fire season and at annual scale occurred in 2006.

Unlike the consistent trends in temperature, precipitation shows a decreasing trend in two stations (Vilyuisk and Verkhnevilyuisk). However, these are not the years with many of the high temperature shifts.

4) Temperature showed significant upward trends at the onset (April-May) and the ending months of the fire season (September-October). Also, significant upward trends were found for annual and seasonal scales and during peak fire period. With regard to precipitation, we found both significant upward and downward trends. However, important for fire weather analysis, significant downwards trends were detected in Vilyuisky and Verkhnevilyuisky districts at the end of the fire season in September. This decreasing precipitation trend in September may extend the fire season, which in turn can increase the cumulative extent of burned area.

The results of our analyses showed the relevance of proposed approach based on measures of magnitude, pace, consistency and significance of changes. We believe that the proposed approach can be used in other fire-prone regions of Russia as well as other boreal areas to detect climate-induced changes in fire weather variability using short-term ranks of meteorological parameters. However, we also believe that more sophisticated statistical analysis tools will deepen the understanding of climate-induced fire weather changes when more data can be analyzed: we will need a more extended period of data into the future as well as a larger network of reporting stations. Also, the proposed climate change analyses for signals of change can help to prepare for and mitigate damage to forests and forestry sector.

The identified fire weather changes and related changes in fire seasonality, strongly suggest a relation to the increase of fire activity. On the basis of our findings we offer the two following recommendations to maintain sustainable forestry and forest fire suppression practices in the Sakha Republic. First of all, it is necessary to start the monitoring of forest fires in April, because in recent years the fire season in the Republic starts earlier; and continue that monitoring until the end of the fire season, in October. Moreover, for effective monitoring and detection of fires is it necessary to use not only ground and aerial observation as it is already done by Yakutian Forestry Service, but also the satellite monitoring of fires, which is now the best tool for the early detection of fire hot spots. The other recommended measure is a close collaboration between the Yakutian Forestry and the Hydrometeorological Services to assess as one way historical and recent fire weather trends to create fire weather and fire risk predictions. The suggested analysis of historical and recent fire weather trends may contribute to finding regional fire-weather and fire-climate cycles. This analysis also may help to build a forest fire vulnerability system for the Sakha Republic. It should also make use of assessments of fire activity and their relationships to the fire weather. We should then be able to see the regional forest forest fire vulnerability assessment, including fire risk zoning and mapping. Finally, a more sophisticated way to maintain effective fire monitoring and suppression practices will need to include a real time hot spot and early fire detection system, for early warning of high fire risk.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendices

Appendix 1. Information on Selected Forestry Districts

Table A1. Information on selected forestry districts.

Forestry District	Type of Forest zone	Relief	Climate	Precipitation, mm	Forest Cover, %	Dominant Tree Species	The Natural Fire Hazard Risk*
Amginsky	Taiga (coniferous boreal forests)	Flat terrain	Sharply continental, dry	200 - 250	83	Siberian Larch, Scots Pine, Siberian Spruce, Silver Birch	2.5
Gorny	Taiga (coniferous boreal forests)	Undulating plain relief	Sharply continental, dry	Up to 270	92	Dahurian larch, Scots Pine, Siberian Spruce, Silver Birch	3.1
Khangalassky	Taiga (coniferous boreal forests)	Gentle slops turning into plateau	Sharply continental, relatively dry	200 - 350	95	Siberian Larch, Scots Pine, Siberian Spruce, Silver Birch	2.4
Verkhnevilyuisky	Taiga (coniferous boreal forests)	Flat terrain	Sharply continental, dry	200 - 250	81	Dahurian larch, Scots Pine, Siberian Spruce, Silver Birch	1.6
Vilyuisky	Taiga (coniferous boreal forests)	Flat terrain	Sharply continental, dry	200 - 300	67	Dahurian larch, Scots Pine, Siberian Spruce, Silver Birch	2.4

*According to The Russian Classification of Natural Forest Fire Hazard Risk (see the URL in the References). Data Source: Forestry-based regulations (Lesohozyaistvennyi reglament, in Russian) of Amginsky, Gorny, Khangalassky, Vilyuisky and Verkhnevilyuisky forestry districts, Department of Forestry of the Sakha Republic (Yakutia), 2017 (see URL in the References).

Appendix 2. Research Design

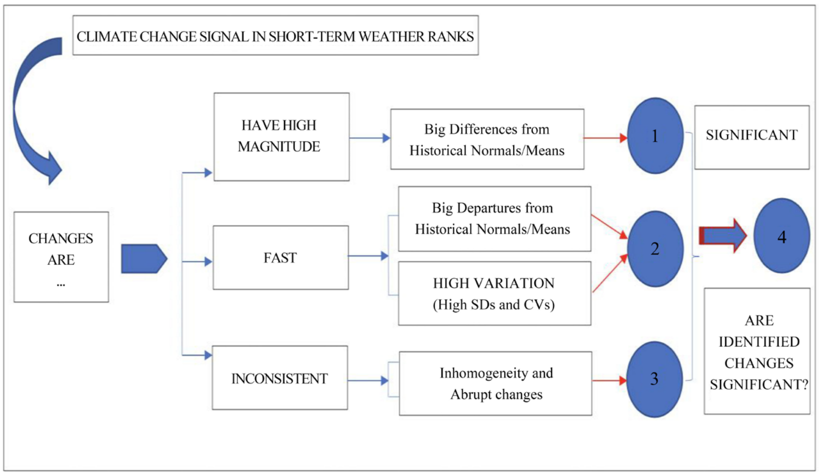
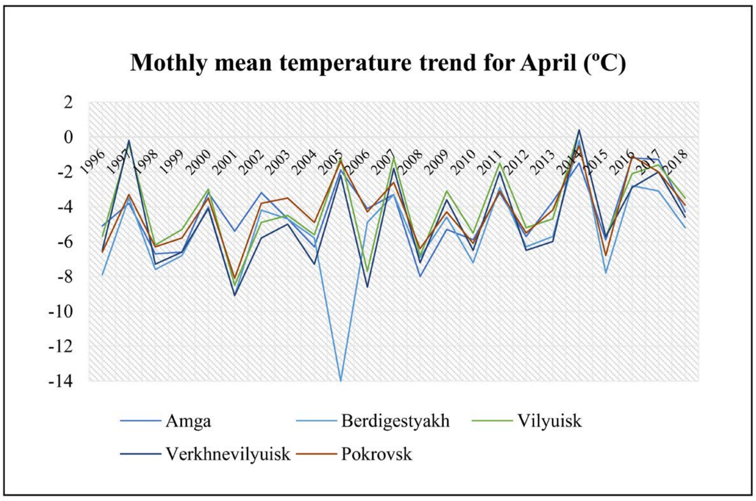
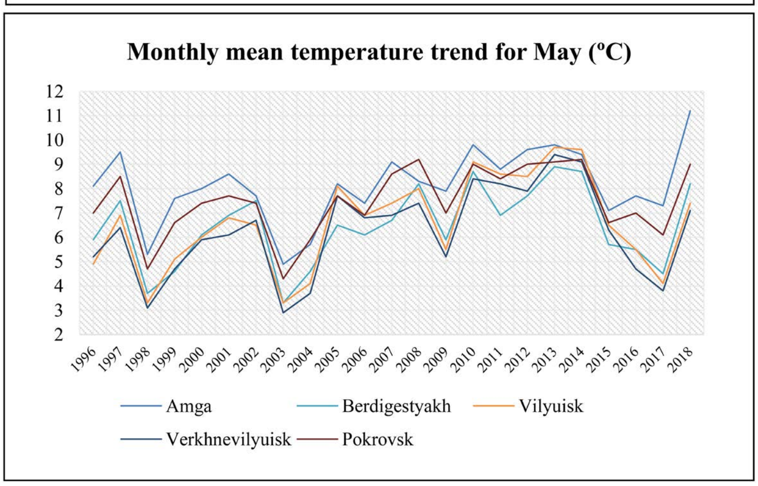
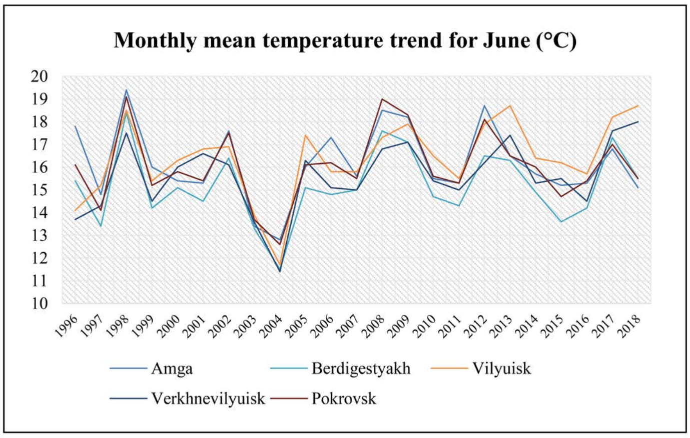


Figure A1. Research Design. *1-4—steps of analyses: 1—descriptive statistics (calculation of historical normals/means and calculation of means for study period, 1996-2018); 2—variability analysis; 3—homogeneity analysis; 4—trend analysis.

Appendix 3. Trends of Temperature and Precipitation across Sakha Republic, 1996-2018






Monthly mean temperature trend for June (°C)
20
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1997
1998
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2003
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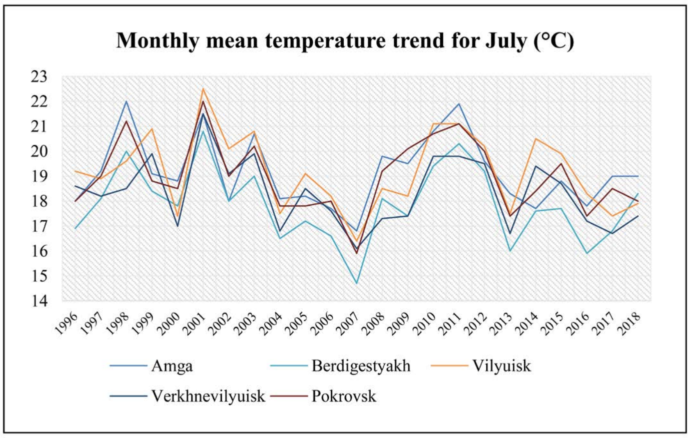
Verkhnevilyuisk
Pokrovsk


Monthly mean temperature trend for July (°C)
23
22
21
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19
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15
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1996
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1998
1999
2000
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2002
2003
2004
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2006
2007
2008
2009
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2017
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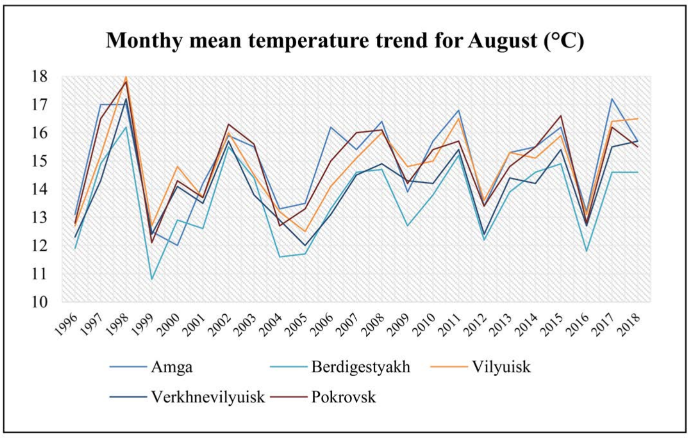
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk


Monthy mean temperature trend for August (°C)
18
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1998
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2004
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Verkhnevilyuisk
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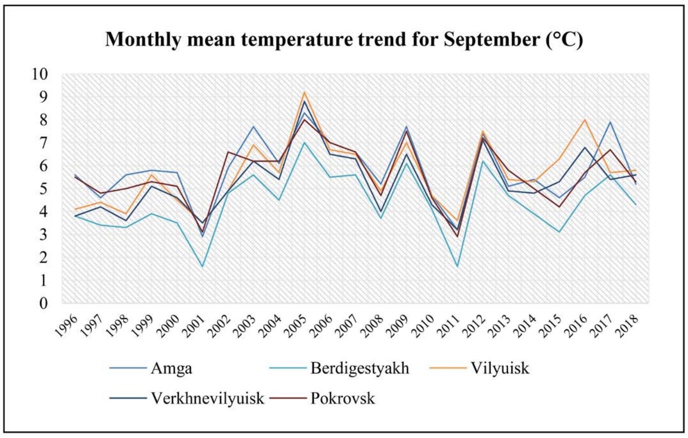
Monthly mean temperature trend for September (°C)
10
9
8
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1996
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Vilyuisk
Verkhnevilyuisk
Pokrovsk

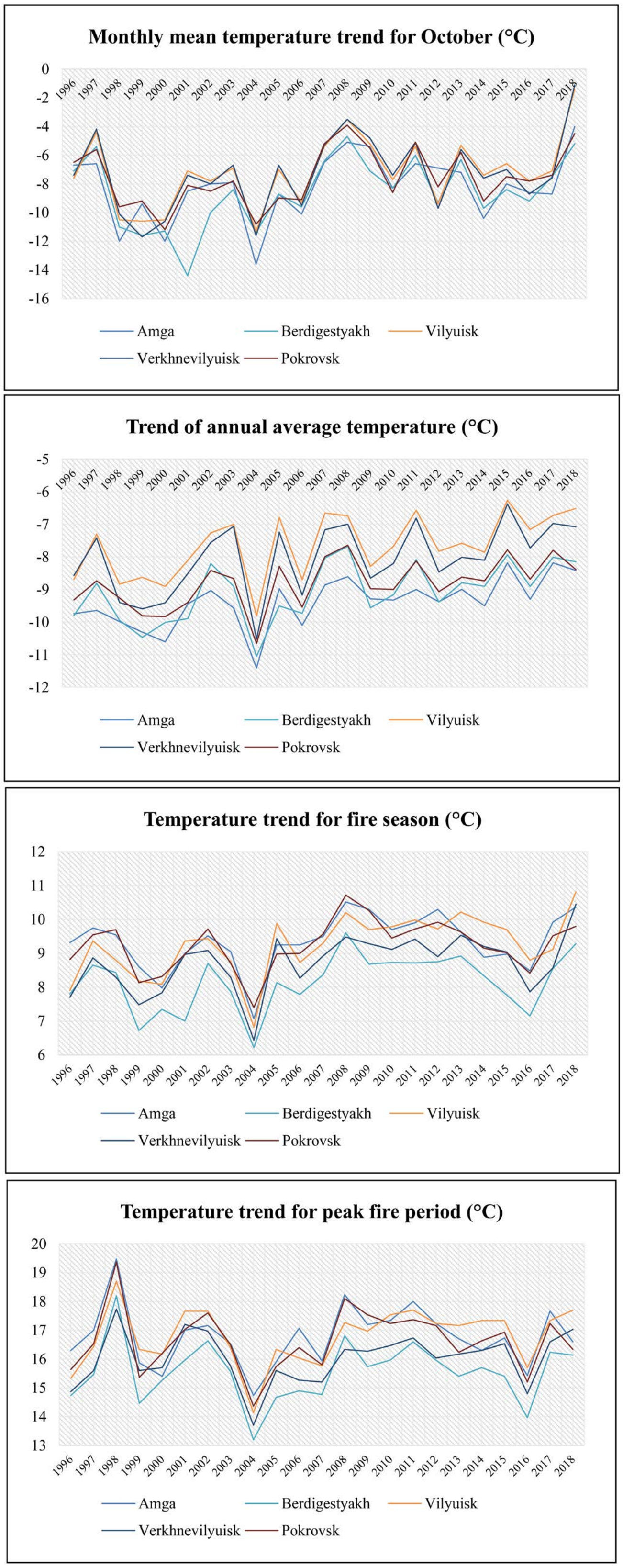
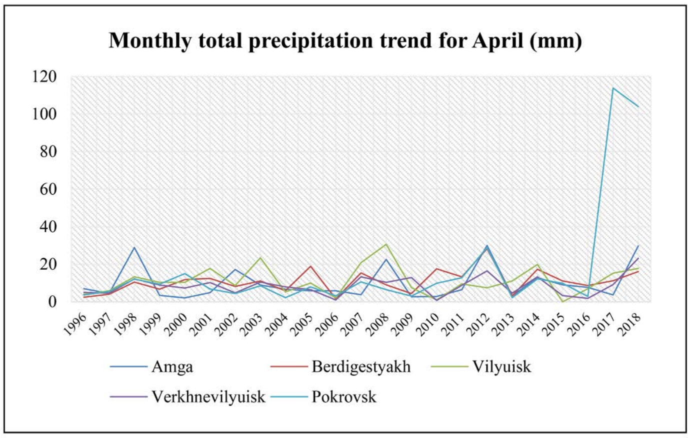
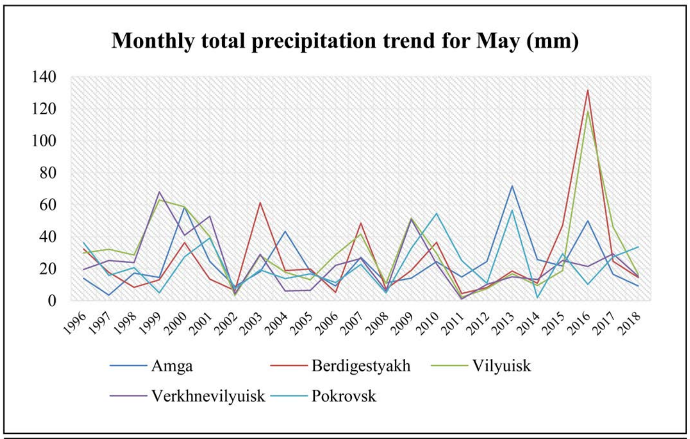
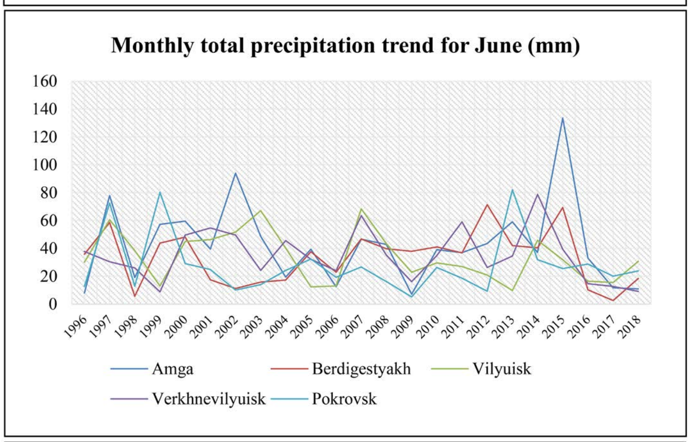
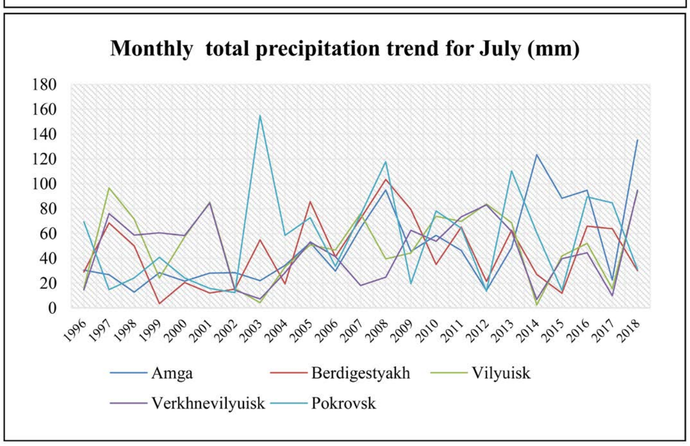


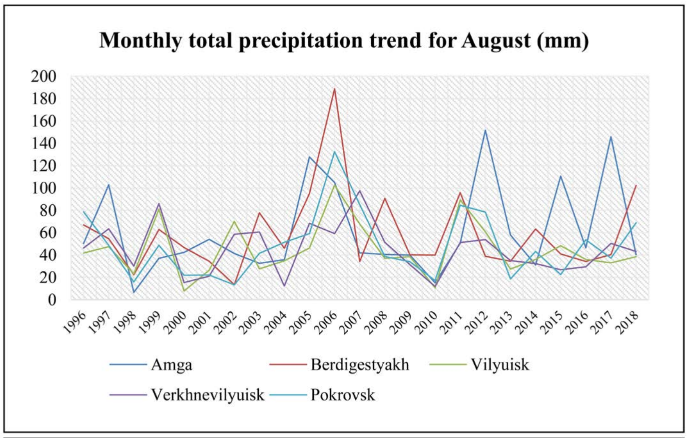
Figure A2. Trends of temperature across Sakha Republic, 1996-2018 (in ˚C). *Berdigestyakh Station, Gorny forestry district—extreme temperature −14˚C (2005) was verified with station data.

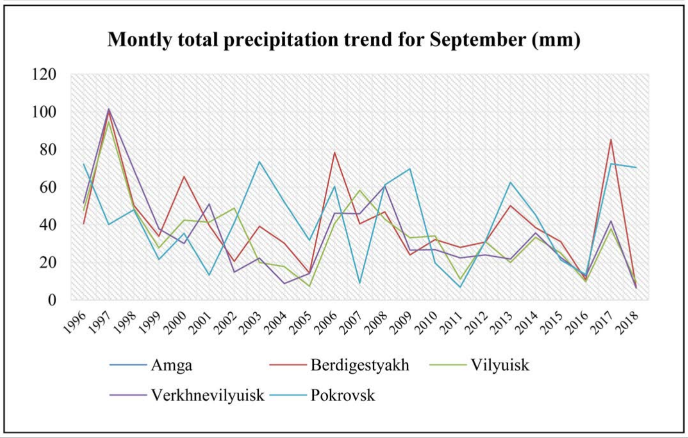

Monthly total precipitation trend for April (mm)
120
100
80
60
40
20
0
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk

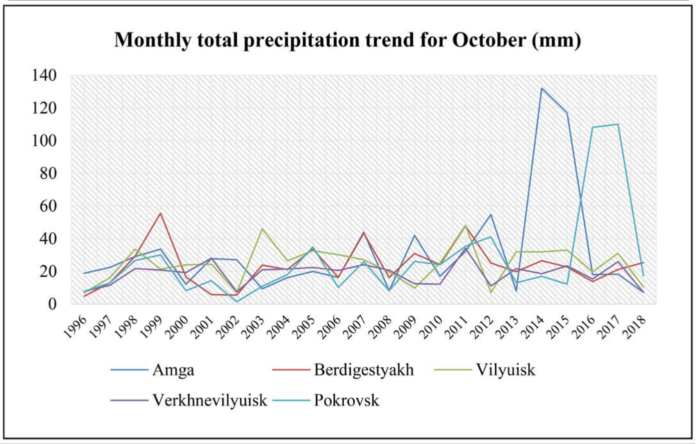

Monthly total precipitation trend for May (mm)
140
120
100
80
60
40
20
0
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk

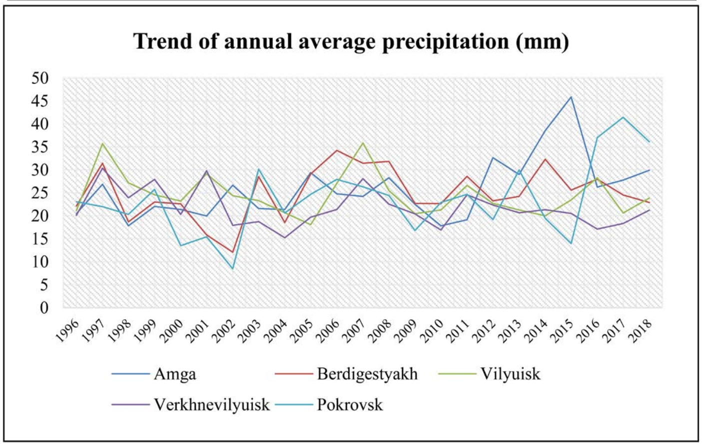

Monthly total precipitation trend for June (mm)
160
140
120
100
80
60
40
20
0
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk


Monthly total precipitation trend for July (mm)
180
160
140
120
100
80
60
40
20
0
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk


Monthly total precipitation trend for August (mm)
200
180
160
140
120
100
80
60
40
20
0
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk


Montly total precipitation trend for September (mm)
120
100
80
60
40
20
0
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk


Monthly total precipitation trend for October (mm)
140
120
100
80
60
40
20
0
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk


Trend of annual average precipitation (mm)
50
45
40
35
30
25
20
15
10
5
0
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Amga
Berdigestyakh
Vilyuisk
Verkhnevilyuisk
Pokrovsk

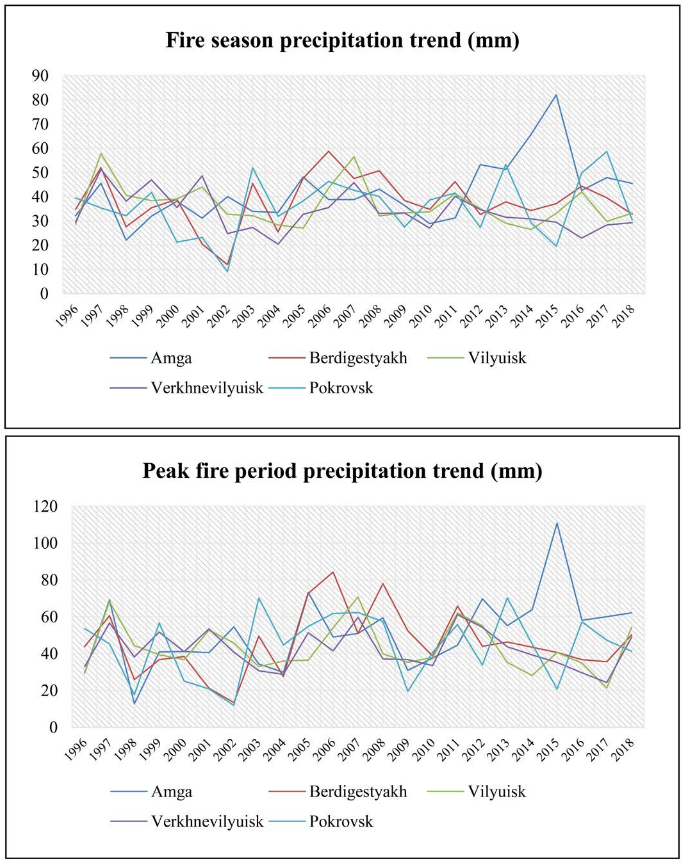


Figure A3. Trends of precipitation across Sakha Republic, 1996-2018 (in mm).