Modern Climate Changes in the North Caucasus Region

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Abstract This article is devoted to the analysis of changes in the air temperature and precipitation regimes in various climatic zones of the North Caucasus region. Time series of seasonal and annual temperatures in the surface layer of the atmosphere and precipitation for the period 1976–2019 were used to study climate change. It was found that in all climatic zones of the North Caucasus region there was a significant increasing in average annual and seasonal temperatures, especially during the summer season. The change in precipitation regime is not as obvious as the change in temperature. In all climatic zones, both an increase and a decrease in seasonal precipitation, mostly statistically insignificant, were observed. The trend resistance of meteorological parameters was assessed using the normalized range method and its quantitative indicator—the Hurst index. The Hurst index, calculated for the average seasonal temperatures and sum of precipitation, showed a high probability of persistence of the trends, especially for summer temperatures and autumn sum precipitation.

Keywords North Caucasus · Climate change · Air temperature · Precipitation

1 Introduction

Much attention is paid to the study of climate change currently. The consequences of climate change can significantly affect the economic development of society and the safety of people's lives. For Russia 2019 was very warm: the fourth among the warmest in a series of observations since 1936: the average temperature for the year was 2.07 °C higher than the climate norm—the average for 1961–1990. The growth rate of the average annual temperature in Russia was 0.47 °C/10 years. Significant

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climatic anomalies were observed during the year. The spring was very warm with the average temperature for the Russian Federation 2.86 °C above the norm: the fourth value during the observation period [1].

Due to the length of the territory of Russia and the diversity of its natural and climatic features, the consequences of climate change manifest themselves differently in different regions [2]. The climatic features of the North Caucasus region are determined by a number of factors, including zonal and altitudinal zonality, and therefore, the region was divided into four zones depending on the height above sea level (a.s.l.): flat (<500 m a.s.l.), foothill (500–1000 m a.s.l.), mountainous (1000–2000 m a.s.l.) and high-mountain (over 2000 m a.s.l.) zones, where climate change can differ significantly. This article is devoted to the analysis of changes in the air temperature and precipitation regimes in different climatic zones of the North Caucasus region in the period 1976–2019.

It is important to identify trends in the dynamics of such natural and climatic characteristics as the temperature regime of air in the surface layer of the atmosphere and the precipitation regime to analyze climate change. Studies are being carried out on the dynamics of temperature, precipitation, humidity and other climate characteristics based on long-term observations to solve this problem.

2 Materials and Methods

It was used data from time series of seasonal and annual temperatures in the surface layer of the atmosphere and precipitation for 1976–2019 to study climate changes in the North Caucasus region: average temperatures, absolute maximum temperatures, absolute minimum temperatures; amount of precipitation, daily maxima of precipitation and number of days with precipitation of at least 20 mm. The initial data of the listed meteorological parameters is the result of primary measurements at the weather stations (w/stations) of the Roshydromet network, provided by the North Caucasian Hydrometeorological Service Department (HSD), as well as data using the electronic resource https://rp5.ru. Time series were studied by methods of mathematical statistics and supplemented with linear trends that characterize the trend of the value under consideration. The studies were carried out for time series of temperature regime and precipitation regime (annual and seasonal) at sixteen considered w/stations. Linear trend coefficients b in our study are expressed in degrees per decade, °C/10 years, or in mm/month/10 years (hereinafter referred to as mm/10 years), D (%) is the contribution to the total variance for 1976–2019.

The quality of the regression model as a whole and by parameters was assessed using the Fisher criterion. The constructed regression equation is significant and can act as a forecast model if the actual value of the Fisher criterion is higher than the theoretical one ($F_{fact}. > F_{theor}.$). The calculation showed that the trend is statistically significant for the coefficient of determination above $R^2 = 0.075$ ($D = R^2 \cdot 100\% = 7.5\%$) for $n = 44$ (for degrees of freedom $df = n - k - 1 = 42$).

An assessment was made of the sustainability of climate change in the course of the study. An indicator of the fractal properties of time series, the so-called Hurst exponent (*H*), was used as its integral characteristic. Most of the time series of meteorological parameters are non-linear [3–5]. Recently, for the study of nonlinear systems, the so-called normalized range method (*R/S*– method or fractal analysis) is used, based on the dependence of the normalized range of the parameter on the magnitude of the time increment. The normalized range value scales as the time increment increases, according to a power-law value commonly referred to as the Hurst exponent (*H*).

The estimate of the Hurst exponent *H* is calculated by the formula:

$$H = \frac{lg(R/S)}{lg(aT)} \quad (1)$$

where *R*—the range of deviations from the mean, *S*—the empirical standard deviation, *T*—the observation period; *a*—the given constant (Hurst empirically calculated this constant for relatively short time series of natural phenomena as $a = 0.5$).

The larger the value *H* ($0.5 < H < 1$), the trend is more persistence and more deterministic. Time sequences with $H > 0.5$ belong to the class of persistent (stable), preserving the effect of long-term memory. The series for which $H = 0.5$ have an independent data distribution, are characterized by zero mean and variance equal to 1. The case of $H < 0.5$ is characterized by antipersistence.

A reliable fact is that warming is uneven in time, in addition, it manifests itself differently in different regions. The climate of the North Caucasus region, in addition to the main climate-forming factors, is greatly influenced by the relief and orography of the area. Table 1 presents the physical and geographical characteristics of 16 w/stations, representing all climatic zones of the North Caucasus region.

The synoptic index, geographic coordinates and height above sea level of weather stations are given using official sources (http://meteomaps.ru/meteostation_codes.html—List of indices of meteorological stations (synoptic index); https://yugmeteo.donpac.ru/Observation/—Stationary observation points for the state of the environment of the Federal State Budgetary Institution “North Caucasian HSD”).

3 Analysis and Discussion

Many papers [6–8] provide various estimates of changes in the global near-surface air temperature. According to our estimates the warming trend throughout the Caucasus region corresponds to the general direction of global temperature change over the study period 1976–2019.

Summary characteristics of the linear trend are presented in Table 2.

Terskol data on absolute maximums and minimums of temperatures are available only since 2006, therefore they were not included in Table 2.

Table 1 Physical and geographical characteristics of weather stations in the North Caucasus region

No n/n	Synoptic index	Weather stations	Geographical coordinates	Height above sea level (a.s.l.), m
Flat stations				
1	34,945	Izobil'nyi (Stavropol region)	41.5° N; 47.8° E	206
2	37,145	Mozdok (Republic of North Ossetia—Alania)	43.7° N; 44.7° E	136
3	37,144	Prokhladnaya (Kabardino-Balkaria)	43.8° N; 44.1° E	199
4	37,470	Derbent (Dagestan)	42.1° N; 48.3° E	−19
5	37,163	Kizlyar (Dagestan)	43.8° N; 46.7° E	−5
6	37,472	Makhachkala (Dagestan)	42.8° N; 47.6° E	32
7	37,473	Izberg (Dagestan)	42.5° N; 47.9° E	−21
Foothill stations				
8	34,949	Stavropol (Stavropol region)	45.1° N; 42.1° E	452
9	37,047	Cherkessk (Karachay-Cherkessia)	44.1° N; 42.0° E	525
10	37,123	Kislovodsk (Stavropol region)	45.5° N; 42.4° E	890
11	37,212	Nalchik (Kabardino-Balkaria)	43.5° N; 43.7° E	432
12	37,228	Vladikavkaz (Republic of North Ossetia—Alania)	43.1° N; 44.6° E	703
13	37,471	Buinaksk (Dagestan)	42.8° N; 47.1° E	473
Mountain stations				
14	37,193	Teberda (Karachay-Cherkessia)	43.4° N; 41.7° E	1325
15	37,663	Akhty (Dagestan)	41.5° N; 47.8° E	1015
High-mountain station				
16	37,204	Terskol (Kabardino-Balkaria)	42.5° N; 43.3° E	2144

There was a further significant increase in average annual and seasonal temperatures in all climatic zones of the North Caucasus region for 1976–2019. The parameters of linear temperature trends given in Table 2 indicate that, according to the growth rate of the average temperature in 1976–2019 warming in all climatic zones of the region in the summer season exceeds the winter, spring and autumn seasons (significantly in the highland zone). The contribution of the trend to the exflated dispersion of air temperature in the summer season is much higher compared to this

Table 2 Characteristics of the linear trend (*b, D*) of the temperature regime at the stations of the North Caucasus region for 1976–2019

Season		Flat zone		Foothill zone		Mountainous zone		High- mountain zone	
		b	***D***	***b***	***D***	***b***	***D***	***b***	***D***
Year	*T*[a]	0.46	**47.2**[b]	0.57	**55.1**	0.43	**44.2**	0.19	**13.6**
	Min	0.37	1.43	0.26	0.87	0.57	**9.83**	–	–
	Max	0.78	**38.6**	0.76	**27.2**	0.51	**10.65**	–	–
Winter	*T*	0.38	**12.2**	0.49	**17.3**	0.47	**13.9**	0.11	0.9
	Min	0.22	0.48	0.61	4.46	0.42	4.93	–	–
	Max	−0.08	0.21	0.35	3.75	0.52	**10.46**	–	–
Spring	*T*	0.41	**29.1**	0.50	**29.8**	0.34	**17.3**	0.16	4.3
	Min	0.76	**9.88**	1.23	**19.24**	1.17	**17.59**	–	–
	Max	0.56	**15.02**	0.44	8.1	0.28	4.76	–	–
Summer	*T*	0.59	**50.2**	0.76	**57.5**	0.53	**48.7**	0.44	**42.1**
	Min	0.33	**8.92**	0.64	**28.51**	0.54	**19.66**	–	–
	Max	0.77	**37.2**	0.75	**25.2**	0.42	7.29	–	–
Autumn	*T*	0.42	**18.9**	0.52	**26.4**	0.37	**17.0**	0.05	0.4
	Min	0.33	1.55	0.62	5.20	0.41	2.82	–	–
	Max	0.61	**20.5**	0.7	**14.3**	0.15	0.68	–	–

[a]T—the average temperature, Min—the absolute minimum, Max—the absolute maximum, b—the value of the slope of the linear trend (°C /10 years), D (%)—the contribution of the trend to the total variance
[b]Trends in bold type are statistically significant at the 5% level.

indicator in other seasons (the highest excess in the high mountain zone, $D = 42.1\%$ in summer and $D = 0.9\%$ in winter).

In the flat, mountain and foothill zones, a statistically significant increase in average annual temperatures occurred during the last years of the period 1976–2019. In the high-mountain zone (Terskol), the average annual temperature growth rate was 0.19 °C/10 years ($D = 13.6\%$), which also characterizes a steady and statistically significant increase in the average annual temperature.

It should be noted that the growth of the average annual temperature throughout the territory of the Russian Federation coincides with the trends in the growth of annual temperature in the North Caucasus region, especially in the flat zone. As for seasonal changes, the most rapid growth across the entire territory of the Russian Federation was observed in spring (0.63 °C/10 years), while against the background of interannual fluctuations, the trend is most pronounced in summer (0.39 °C/10 years: describes 63% total variance) [1]. In contrast, in the region under consideration, the fastest growth was observed in summer for all climatic zones: from 0.44 °C/10 years ($D = 42.1\%$) in the high mountain zone to 0.76 °C/10 years ($D = 57.5\%$) in the foothill zone.

In the flat and foothill zones, the growth of average annual temperatures occurred due to the growth of summer and autumn absolute maxima, as well as the growth of spring and summer absolute minima. An increase in spring absolute maximum temperatures was observed only in the flat zone. The increase in the growth of average annual temperatures in the mountain zone occurred due to the growth of winter absolute maxima and the growth of spring and autumn absolute minima. Since the minimum temperatures occur at night, their increase in the spring season leads to a decrease in night frosts. A consequence of the rise in spring lows is that spring warmth arrives earlier, and rising mean summer temperatures drag out summer conditions, shortening autumn.

The change in the precipitation regime is not as obvious as the change in the temperature regime, and, in general, is not statistically significant. In all climatic zones, both an increase and a decrease in seasonal precipitation were observed. Table 3 and Fig. 2 present the characteristics of the linear trend *b* (*D*) for 1976–2019 some indicators of the average annual and average seasonal precipitation regime.

In all climatic zones of the North Caucasus region, there was a statistically insignificant increase in annual precipitation. The highest growth rate was in the high-mountain zone ($b = 15.25$ mm/10 years, $D = 1.36\%$). In the flat and foothill zones

Table 3 Characteristics of the linear trend (*b*, *D*) of the precipitation regime at the stations of the North Caucasus region for 1976–2019

Season		Flats zone		Foothill zone		Mountain zone		High-mountain zone	
		b	***D***	***b***	***D***	***b***	***D***	***b***	***D***
Year	*R*[a]	5.32	1.12	0.93	0.01	6.55	1.2	15.25	1.36
	Max	1.1	1.59	−0.04	0.0	0.72	0.91	–	–
	NR20	0.05	0.28	0.08	0.49	−0.15	1.23	–	–
Winter	*R*	5.21	**9.62**[b]	2.47	2.87	0.042	0.0	−3.02	0.25
	Max	0.39	2.02	0.43	3.61	−1.13	3.16	–	–
	NR20	0.02	1.33	0.02	3.8	−0.08	1.33	–	–
Spring	*R*	2.27	1.64	7.27	6.04	10.01	8.9	12.89	3.52
	Max	0.46	0.62	0.02	0.0	0.42	0.36	–	–
	NR20	0.07	3.54	0.1	3.12	0.15	5.1	–	–
Summer	*R*	−4.45	3.0	−7.95	2.75	−2.25	0.6	0.57	0.01
	Max	0.47	0.56	0.42	0.38	−0.59	0.81	–	–
	NR20	−0.13	6.79	−0.06	0.46	−0.2	8.04	–	–
Autumn	*R*	3.12	1.08	−0.34	0.01	−0.66	0.03	5.7	0.66
	Max	1.1	2.23	−0.25	0.29	0.13	0.05	–	–
	NR20	0.1	3.58	0.01	0.02	−0.02	0.05	–	–

[a]R—the precipitation sum, Max—the maximum daily precipitation, NR20—the number of days with precipitation of at least 20 mm, b—the value of the slope of the linear trend (mm/10 years for R and Max; n/10 years for NR20), D (%)—the contribution of the trend into the total variance
[b]Trends in bold type are statistically significant at the 5% level.

the seasonal totals of precipitation in the period 1976–2019 had a positive trend in all seasons, with the exception of summer, where a negative trend was observed. In the mountain zone the negative trend took place in the summer and autumn seasons. The high-mountain zone, unlike the others, is characterized by increase in summer precipitation and decrease in winter precipitation. All changes in precipitation amounts are statistically insignificant, except for the positive trend in the winter season in the flat zone ($b = 5.21$ mm/10 years, $D = 9.62\%$).

Daily precipitation maxima in the flat zone tended to decrease in the autumn and winter seasons, while the summer season is characterized by their growth. Thus, the change in precipitation in response to summer warming was uneven, and this happened mainly during events that are considered extreme.

In the foothill zone daily precipitation maxima decreased in all seasons and in the year as a whole. In the mountainous zone significant decrease in daily precipitation maxima was also observed, especially in the winter season.

In all seasons of the period 1976–2019 in all climatic zones, there was a statistically insignificant increase (50%) and decrease (50%) in the *NR20*.

The normalized range method (fractal analysis) was used to determine the stability of changes in meteorological parameters, for which the Hurst index was calculated using formula 2. The values of the Hurst exponent for average temperature and precipitation in each climatic zone are shown in Table 4.

The Hurst exponent obtained for the series of average annual temperature in the period 1976–2019 took values from $H = 0.5$ in the high-mountain zone in autumn to $H = 0.9$ in the summer in the foothill zone, for the series of precipitation amounts, the Hurst exponent varied from $H = 0.54$ in winter to $H = 0.83$ in spring in the mountain zone, which demonstrates the high trend persistence of the series.

In our work, both in studies [9–11], stability indicators for temperature ($0.68 \div 0.90$) exceed values for precipitation ($0.54 \div 0.74$), which characterizes longer-term changes in air temperature regime compared to precipitation. Our results show that the precipitation series, and especially the temperature series, is not a perfect

Table 4 Values of the Hurst exponent

Season	Flat zone	Foothill zone	Mountainous zone	High-mountain zone
Average temperature				
Winter	0.68	0.76	0.72	0.67
Spring	0.79	0.77	0.70	0.61
Summer	**0.89**	**0.90**	**0.87**	**0.86**
Autumn	0.78	0.81	0.73	0.50
Amount of precipitation				
Winter	0.69	0.64	0.54	0.55
Spring	0.55	0.67	0.73	0.74
Summer	0.55	0.60	0.61	0.58
Autumn	0.67	0.73	0.71	0.73

Poisson process ($H = 0.5$), on the contrary, there is some long-term correlation between subsequent events and initial ones. Thus, the change in these meteorological parameters, as a phenomenon, carries the dual characteristics of randomness and regularity, and the more H deviates from 0.5, the more regularity appears in the time series.

4 Conclusions

The conducted studies showed that for the studied period 1976–2019 in all climatic zones of the North Caucasus region, there was a further significant increase in average annual and seasonal temperatures. According to the growth rate of the average temperature in 1976–2019 warming in all climatic zones of the region in the summer season exceeds the winter, spring and autumn seasons. The contribution of the trend to the explained variance of air temperature in the summer season is much higher compared to this indicator in other seasons.

The change in the precipitation regime is not as obvious as the change in the temperature regime. In all climatic zones, both an increase and a decrease in seasonal precipitation were observed, mostly statistically insignificant.

The Hurst exponent calculated for the series of seasonal average temperatures and precipitation totals in the period 1976–2019 showed a high probability of continuation of the identified trends, especially for summer temperatures and autumn precipitation totals.

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