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Modern changes in the precipitation and air temperature regime in the mountainous regions of the Dagestan Republic

E. A. Korchagina*, [1]

[1] *Federal Scientific Center "Kabardino-Balkarian Scientific Center of the Russian Academy of Sciences", Nalchik, Russia*

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The study focuses on the local dynamics of precipitation and temperature in the mountainous regions of the Dagestan Republic (North Caucasus, eastern part). A shift in the secondary maximum of the precipitation annual distribution in the low-mountainous part of the region from August to September was found. The wettest years in the highlands in the periods 1966–1978 and 1996–2013 are discovered. The period from the beginning of the current century until now is identified as the wettest in the low-mountain zone. It was found that the trends of seasonal temperatures are positive. At the same time, the dynamics of spring temperatures remained insignificant in the low-mountain zone until 2010. It was revealed that the statistically reliable increase of temperature in February and March and unidirectional tendencies in the daily characteristics of precipitation is the local pattern of the climate change in this part of the North Caucasus. In this season the increase in the average and maximum daily precipitation intensity is reliable.

Keywords: precipitation dynamics, air temperature trends, North Caucasus, East Caucasus, climate change in mountainous areas, natural hazard.

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1 Introduction

Changes in extreme values of atmospheric precipitation and air temperature are the most tangible consequences of global warming. At the same time, the regional dynamics remains not fully clarified, especially in details. With an increase in the values of these climatic characteristics, an increase in the number of floods and associated threats to the population and economy is expected. The qualitative nature of changes in the precipitation regime with an increase in air temperature varies greatly from area to area [*Malygina et al.*, 2017], [*Korchagina*, 2019].

It was established that the kind of the relationship between temperature growth and extreme precipitation differs greatly from region to region and depends on humidity. For the United States, it was found that in regions with high humidity, climate warming leads to an increase in extreme precipitation. There is an inverse relationship in arid regions [*Prein et al.*, 2017].

It is noted that positive trends in extreme precipitation were found for most weather stations outside of Russia. At the same time, the tendencies towards a decrease in the amount of precipitation prevail on the territory [*Yin et al.*, 2018]. It was found that across Russia the number and duration of periods without rain increased in the summer [*Tashilova et al.*, 2019].

A characteristic feature of North Caucasus is the presence of stable trends in annual and seasonal air temperatures and the absence of significant trends in annual precipitation [*Korchagina*, 2018], [*Trenberth*, 2011].

Among the reasons for the increase in the natural hazards frequency are a change of the atmospheric circulation patterns [*Malygina et al.*, 2017], an increase in atmosphere moisture availability caused by rising temperature [*Konapala et al.*, 2017], anthropogenic influence [*Ye and Fetzer*, 2019].

The complex relief and special characteristics of the climate largely determine the spatial distribution of natural processes that damage the eco-

*Corresponding author: helena.a.k@mail.ru

nomic activities of the southern Russia population. Studies on changes in climatic indices are relevant because of their influence on the activity and frequency of dangerous phenomena inherent mountainous regions, such as avalanches, mudflows, landslides, high floods. Climate change issues in the North Caucasus are closely related to the problem of the intensification of dangerous phenomena in mountainous areas. The hydrological regime in the mountains is an important factor in the formation of floods, mudflows, landslides in mountain areas. Globally, climate change has an ambiguous effect on the number of adverse hydrological events [*Sharma et al.*, 2018; *Wasko and Sharma*, 2017; *Blöschl et al.*, 2019]. A similar situation was revealed at the regional level in the North Caucasus [*Rets et al.*, 2018].

In the mountainous regions of the North Caucasus, the formation of the mountain rivers runoff is influenced not only by the rainfall totals, but also by the soil moisture, the conditions during spring-summer period of the high water, etc.

The study of regional changes in air temperature and precipitation is relevant for understanding the ongoing processes and assessing the possible consequences of existing climate trends for the economy and population security.

In this work, the mountainous and low-mountain regions of the Dagestan Republic have been investigated. The dynamics of the average monthly air temperature and monthly totals of atmospheric precipitation is considered. Particular attention is paid to the dynamics of the monthly and seasonal average daily and maximum daily precipitation.

2 Materials and methods

When analyzing the dynamics of time series, the quality of the initial data plays the most important role. To calculate climatic characteristics, such quality is possessed by data presented in specialized arrays of Russian Research Institute of Hydrometeorological Information - the World Data Center [*Bulygina and Razuvaev*, 2012]. Weather stations selected for the database are recommended to track modern changes in climate. The mountainous zone of the Dagestan Republic is represented by two meteorological stations: Sulak, alpine, located at 2927 m above sea level, 42° 22' N, 46° 15' E, and Akhty, 1016 m above sea level, 41° 28' N, 47° 45' E.

The series most satisfying the completeness requirement [*WMO*, 2017] have been compiled since 1932. Since 1966 the data meets the requirements of homogeneity, for a reason the modern method of measurements at meteorological stations was established. The period since 1976 is under close scrutiny of scientists, because it is considered the beginning of intense climate warming. Climate dynamics was investigated for the three periods indicated above.

Statistical modeling and regression analysis were used as methods for studying the dynamics of climatic characteristics time series. More details can be found in [*Trenberth*, 2011; *Korchagina*, 2021]

One of the tasks of this work is to compare the dynamics of average seasonal (monthly) temperatures and the precipitation totals for different seasons. Such characteristics have very different absolute values and measurement scales. In this regard, the series have been transformed to a new form by the procedure of centering and normalizing to the standard deviation. The resulting procedure allows one to obtain series in dimensionless units, all levels of which are in the same range.

3 Results

3.1 Observed changes in precipitation and temperature in the mountainous zone of the Dagestan Republic

The first idea of the climatic characteristics dynamics is provided by the analysis of changes in its annual course. The annual course of precipitation and air temperature reflects not only their regime, but also the intra-annual course of hazardous hydrological and meteorological processes. This climatic characteristic is calculated on the basis of long-term data. Average monthly precipitation totals are calculated over 30-year periods with a 10-year shift.

The annual course of precipitation in the alpine zone (the Sulak meteorological station) has a maximum in May from 1941 to 1990, which includes the base period 1961–1990 used to monitor climate change. Since 1971, the maximum annual precipitation has been in June and over the past thirty years has reached 15.4% of the total annual precipitation and has become pronounced.

The annual course of precipitation, calculated from the data of the Akhty meteorological station, is shown in Figure 1.

The minimum annual rate is in January. Since 1951, there has been a tendency for the precipitation totals to increase in February and March and to decrease in April.

In contrast to the alpine zone, the annual distribution of precipitation according to the data of the Akhty meteorological station has two maxima. The primary maximum falls on June, is pronounced and amounts to 15.2–16.7% of the total annual amount. The secondary maximum changed its position between August and September and in 1961–1990 and 1971–2000, on average, fell on Au-

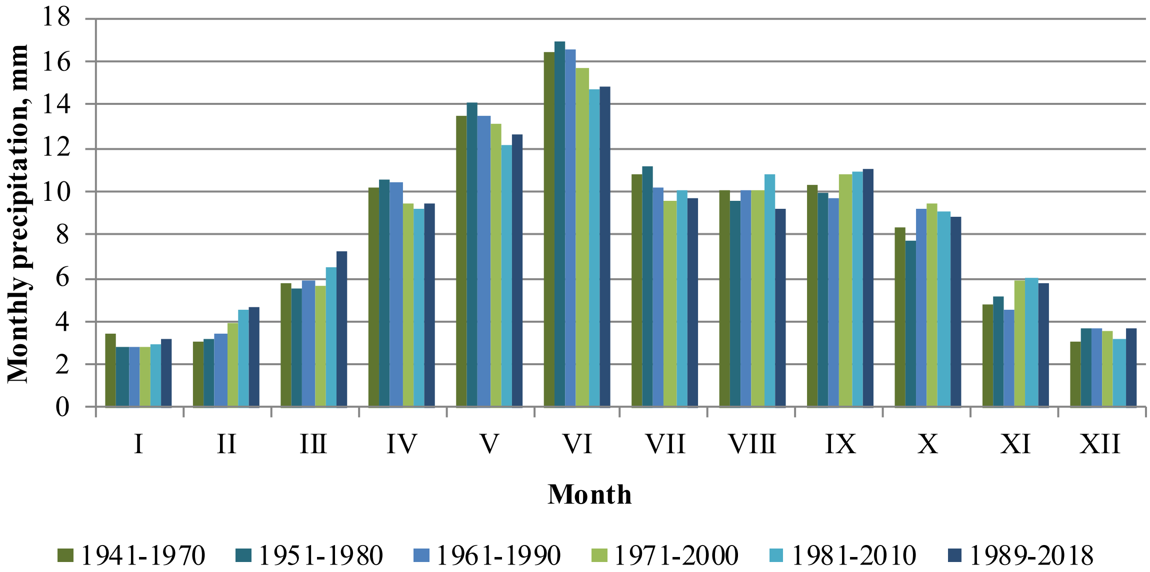

Figure 1: Annual variation of precipitation, Akhty meteorological station.

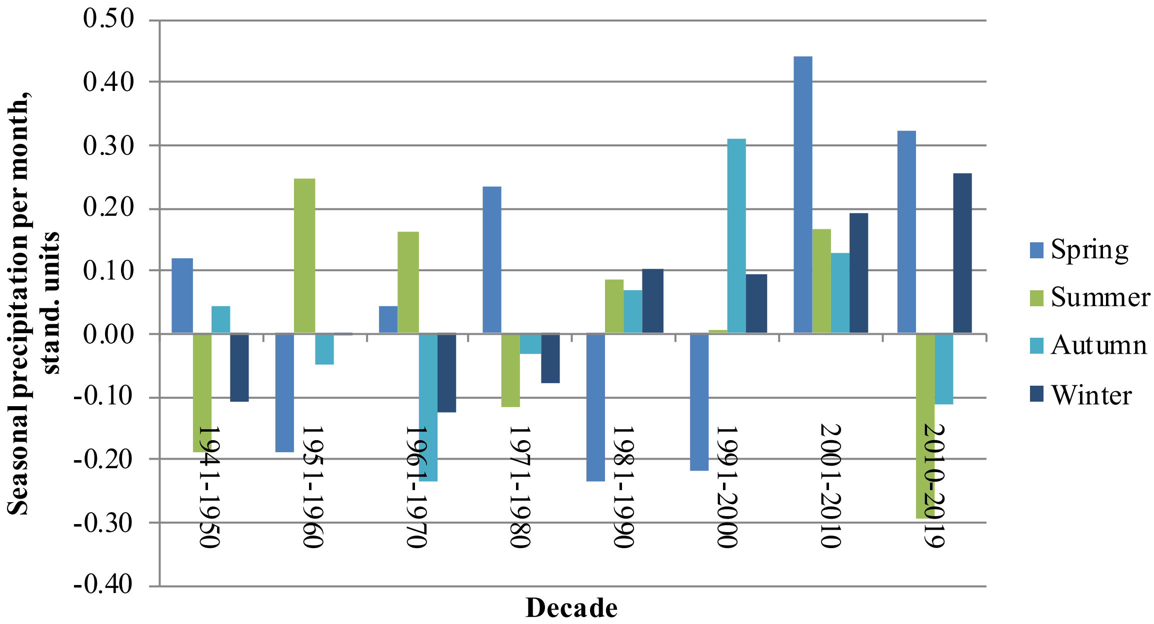

Figure 2: Monthly precipitation totals, Akhty meteorological station.

gust. The latest levels of the series, from 1981–2010 to the present, show that the secondary maximum is well pronounced in September and accounts for 11.3% of the total precipitation.

The dynamics of the seasonal variation was investigated on the basis of the characteristic series averaged over decades. Figure 2 and Figure 3 show the seasonal precipitation variation for standardized series.

The seasonal variation of normalized precipitation anomalies in the high-mountain zone is better coordinated than in the low-mountain zone. The minimum annual precipitation in the high mountain regions falls on 1991–2000 (74 mm/month). The reason for this is the winters with little snow and the dry off-season. In low-mountain areas, the minimum was found in 1931–1940 and may be due to underestimation of the precipitation amount because of the outdated data obtaining method at meteorological stations before 1965. The secondary minimum falls on 1961–1970 due to the negative anomalies of autumn-winter precipitation.

The maximum value of annual precipitation in high mountain regions falls on 1961–1970. All seasonal indices exceed the norm, especially snowy winters and spring. In the low-mountainous region of the republic, the wettest

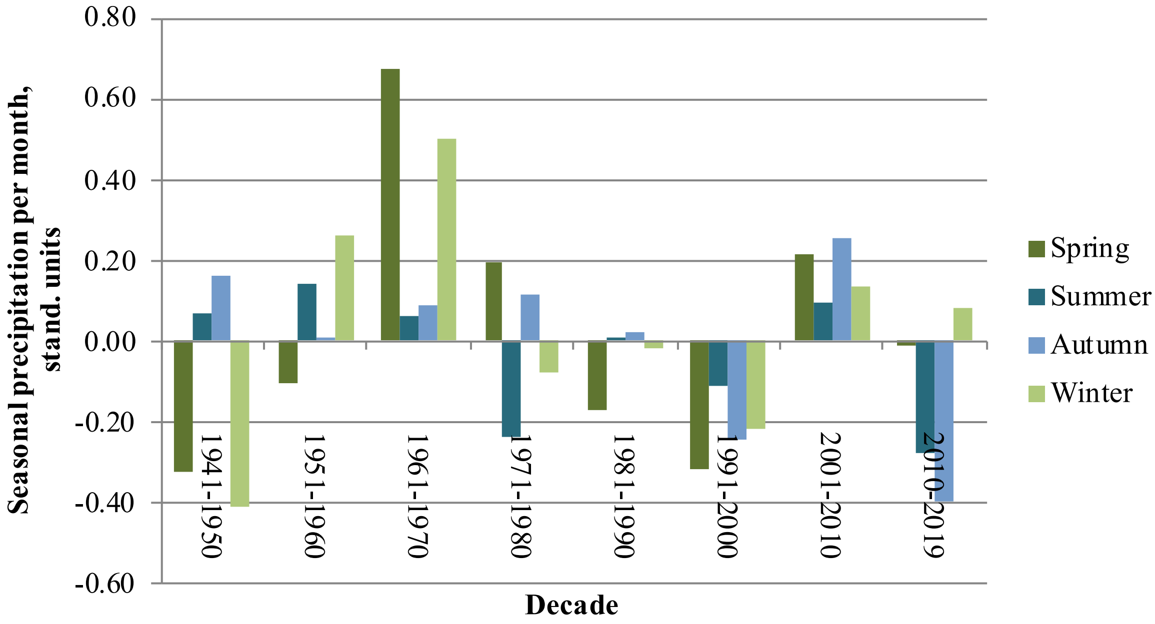

Figure 3: Monthly precipitation totals, Sulak Weather Station.

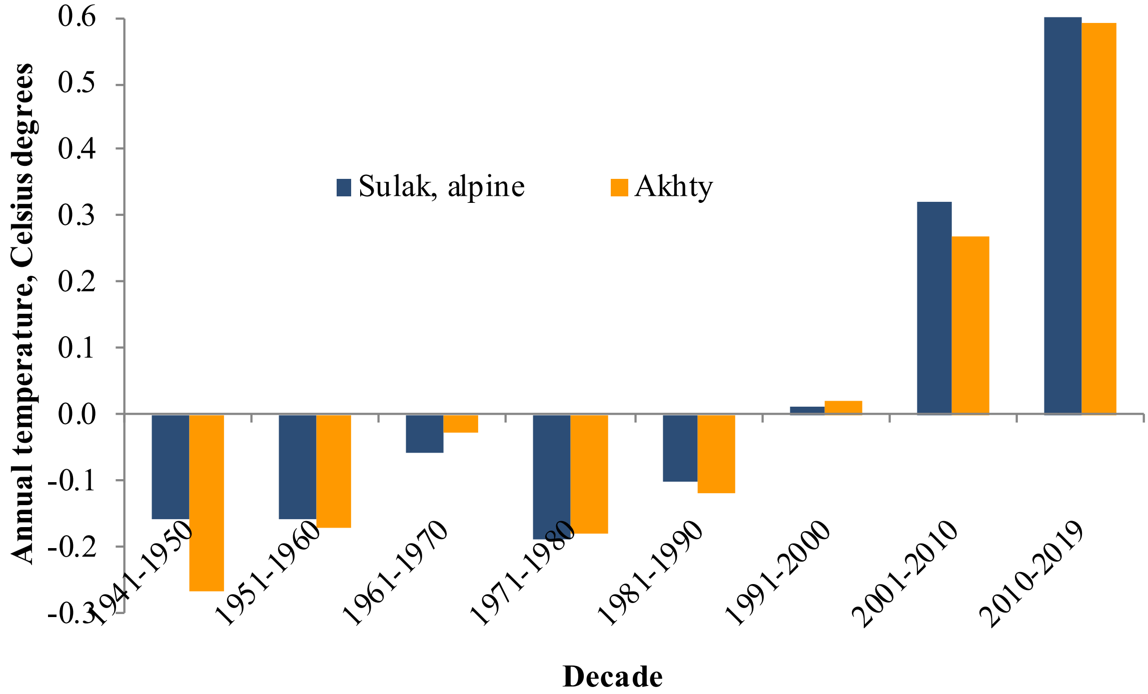

Figure 4: Annual temperatures, standardized units.

decade was 2001–2010. Parallel in time, at the meteorological station Sulak, alpine, a secondary maximum of precipitation is noted.

Summarizing the results of ranking the series of seasonal and annual precipitation levels, we can conclude that the wettest years in the highlands fell on the periods 1966–1978 and 1996–2013. In the low-mountain zone, the wettest period continues to the present.

Comparison of the dynamics of the average annual air temperature in the high-mountain and low-mountain parts of the region is shown in Figure 4.

The temperature field has high connectivity, so their dynamics behavior in different altitude zones is similar. The high spatial correlation of temperature fields in the North Caucasus explains the uniform nature of its dynamics at the meteorological stations of the Eastern Caucasus.

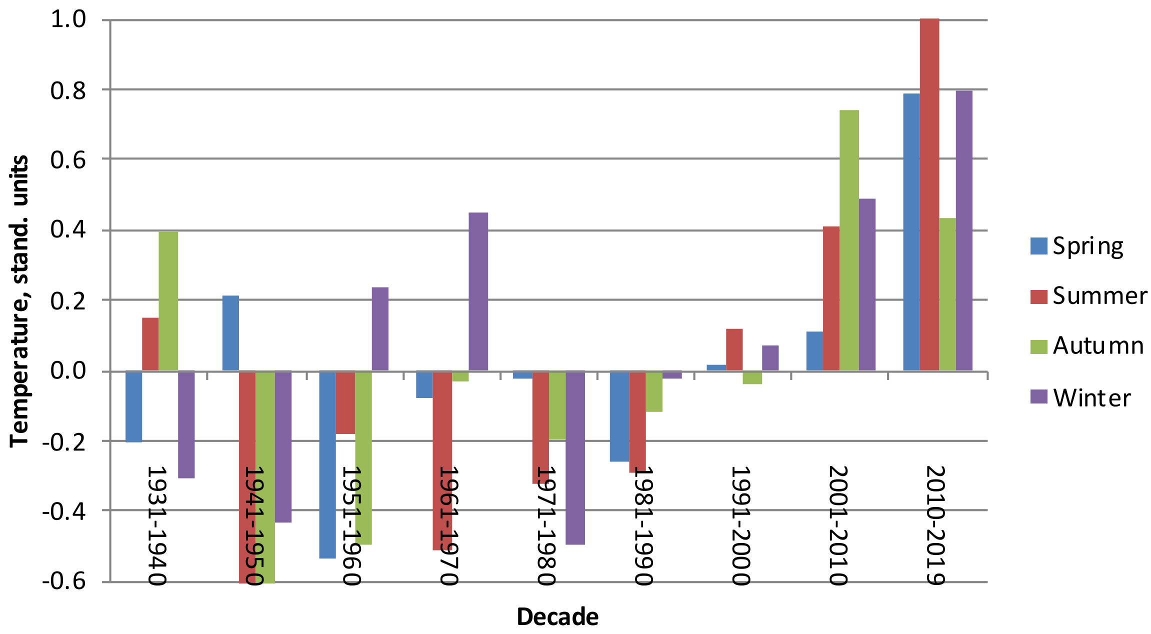

Figure 5: Seasonal averaged temperatures, Akhty weather station.

Seasonal detailing of temperature dynamics in the low-mountain zone according to the data of the Akhty meteorological station are shown in Figure 5.

In the low-mountain zone, the coldest decade was 1941–1950. The summer level of 1991–2000 after a long period of negative values (1941–1990) returned to the values of the beginning of the series: $t^{Summer}_{1931-1940} = 0.07$.

By the end of the period, the summer level reached a value close to unit ($t^{Summer}_{2010-2019} = 0.95$). But autumn temperatures have a maximum in 2001–2010 ($t^{Autumn}_{2001-2010} = 0.54$). The last level of 2010–2019 differs little from the level of the period beginning: $t^{Autumn}_{2010-2019} = 0.33$, $t^{Autumn}_{1931-1940} = 0.3$.

The decade 2010–2019 has the warmest winter seasons.

3.2 Trends in temperature and precipitation

Modeling of linear trends in time series was carried out for such characteristics of atmospheric precipitation as their monthly average seasonal amounts, average daily intensity, the number of days with precipitation of more than 1 mm, more than 5 mm, and more than 20 mm.

Estimates of the linear regression equation that were considered significant at the 0.05 level are shown in Table 1 (alpine zone).

In the highland zone from 1966 to 2018, the trends in February, March, July, October and December are positive. Trends for the rest of the months are negative. At the same time, only a decrease in the amount of precipitation in April ($b^{April}_{1966-2018} = 3$) is reliable at the level of 0.05.

For the low-mountain part, the values of the linear trends are shown in Table 2.

In addition to the values given in Table 2, it was also found that in the time intervals 1966–2018 and 1976–2018, a statistically significant decrease in the number of days with precipitation of more than 30 mm in April and August is −0.2 days / 10 years.

In low-mountainous regions in 1966–2018 the precipitation totals trends are positive from September to March and in July. Only the precipitation increase in March is reliable, $b^{March}_{1966-2018} =$ 3 mm / decade.

During the period of intense global warming since 1976, the precipitation increase in March is reliable at two meteorological stations. The growth rate is close in value and is 11 mm / 10 years according to the Sulak alpine weather station and 10 mm / 10 years according to the Akhty meteorological station.

Thus, an increase in various monthly and daily characteristics of the precipitation in March and July, as well as a decrease in some daily characteristics in April, can be attributed to the regional trend in the change in the precipitation regime in the mountainous regions of the Dagestan Republic.

The local features of the dynamics should include a decrease in the number of days with precipitation of more than 1 mm in May (1932–2019) and in June (1966–2019) in the alpine zone. In the low-mountain zone, the most striking local features are expressed by an increase in various average monthly and daily precipitation characteristics in January and February.

Table 1: Estimates of atmospheric precipitation linear trends, weather station Sulak.

Periods, years	Precipitation amounts, mm / month / 10 years		Days with precipitation over 1 mm, days / 10 years		Average daily intensity, mm / day / 10 years	
	month	value	month	value	month	value
1932–2018	March December	4.7 1.9	March May	0.3 −0.4	all Seasons	0.2–0.5
1966–2018	April	−1.0	June	−2.1	March	0.46
1976–2018	March	1.2	March	0.8	March July	1.1 0.8

Table 2: Estimates of linear trends of atmospheric precipitation, weather station Akhty.

Characteristic	1932–2018		1966–2018		1976–2018	
	month	value	month	value	month	value
Days with precipitation over 1 mm, days / 10 years, N_1			May	0.5	March	0.6
Days with precipitation more than 5 mm, days / 10 years, N_5	January March December	0.2 0.3 0.2	July	0.7	January March July	0.5 0.7 0.8
Days with precipitation over 10 mm, days / 10 years, N_{10}	March Winter	0.2 0.1			March July	0.6 0.5
Maximum daily intensity, mm / day / 10 years P_{max}	February March	0.7 0.5	March April	1.2 −1.2		
Average daily intensity, mm / day / 10 years P_{mean}	February March November	0.3 0.2 0.2	February March April	0.4 0.4 −0.3		

The characteristics of the calculated linear trends of the average monthly and seasonal air temperature in the low-mountainous part of the studied region are shown in Table 3. The estimates of linear trends, statistically significant at the level of 0.05, are shown in bold.

In the low-mountain zone for the period 1966–2019, all trends are positive, with the exception of November. Warming trends for the period February and March are statistically significant.

In the 1976–2019 interval, the trends in the average monthly air temperature are positive throughout the year. The exception is April. Its trend is negative, but not statistically significant. The temperature rise from November to January is also unreliable.

4 Conclusion

The study of local and regional climate dynamics is an urgent task in the era of rapid climatic changes and is associated with the problem of dangerous natural phenomena. For the high-mountain and low-mountain parts of the Dagestan Republic, the following trends have been identified.

In the alpine zone, local changes in dynamics are expressed in a decrease in the number of days with precipitation of more than 1 mm in May (1932–2019) and in June (1966—2019). In the low-mountain zone, the most striking local features are expressed by an increase in various average monthly and daily precipitation characteristics in January and February. Since 1966, there is a statis-

Table 3: Characteristics of air temperature linear trends, Akhty weather station.

Month, season	1931–2019		1966–2019		1976–2019	
	b,°C/decade	p-value	*b*,°C/decade	p-value	*b*,°C/decade	p-value
January	**0.22**	0.04	0.33	0.17	0.46	0.09
February	0.12	0.31	**0.52**	0.04	**0.69**	0.03
March	**0.29**	0.00	**0.61**	0.00	**0.84**	0.00
April	0.14	0.09	0.01	0.97	−0.04	0.86
May	0.05	0.40	0.22	0.06	**0.51**	0.00
June	**0.15**	0.01	**0.43**	0.00	**0.57**	0.00
July	**0.10**	0.04	**0.36**	0.00	**0.44**	0.00
August	**0.12**	0.04	**0.45**	0.00	**0.58**	0.00
September	0.12	0.08	**0.40**	0.01	**0.33**	0.04
October	0.09	0.28	**0.36**	0.04	**0.63**	0.00
November	0.09	0.32	−0.18	0.34	0.01	0.97
December	0.20	0.07	0.21	0.34	0.28	0.35
Year	**0.14**	0.00	**0.31**	0.00	**0.44**	0.00
Spring	**0.16**	0.00	**0.28**	0.01	**0.44**	0.00
Summer	**0.13**	0.00	**0.41**	0.00	**0.53**	0.00
Fall	0.10	0.08	0.19	0.12	**0.32**	0.02
Winter	**0.18**	0.01	**0.35**	0.03	**0.48**	0.01

tically significant decrease in the number of days with high intensity precipitation in August.

Given the absence of significant changes in the average annual precipitation, it can be concluded that the redistribution of precipitation within the annual cycle. Since 1966, in March, there has been an increase in daily characteristics in the low-mountain zone; in the high-mountain zone, this has led to an increase in monthly amounts, too. At the same time, in April, daily precipitation decreases in both zones; in the high-mountainous zone, this is accompanied by a decrease in monthly amounts. Since 1976, in July, the number of days with precipitation of more than 10 mm has been increasing, which is accompanied by a decrease in their number in August, and in the highland zone also in June.

An increase in various monthly and daily precipitation characteristics in March and July, as well as a decrease in some daily characteristics in April and August, is the regional climate change pattern for the mountainous territory in the Greater Caucasus eastern part. Positive air temperature trends are also regional characteristics.

The surface air temperature in the low-mountainous part of the republic shows positive trends throughout almost the entire year (with the exception of November). Attention is drawn to the statistical reliability of the temperature rise in February and March, accompanied by a unidirectional trend of daily precipitation characteristics in this part of the republic. Here, the increase in the average and maximum daily precipitation intensity for the month is reliable. Also noteworthy is the tendency for the air temperature to decrease here in April, although it is statistically insignificant, but is accompanied by a significant decrease in the monthly average daily precipitation intensity. This shows the nature of the air temperature dynamics influence on the precipitation regime in the studied region.

The positive trend in the intensity and frequency of precipitation in July with the background of a sharp increase in warming since 1976 in this month creates conditions for the formation of mudflows and high floods in the mountains of the Eastern Caucasus. Since 1976 in March, the rate of temperature rise is the highest and is estimated at 0.8 °C / 10 years. This process is accompanied by an increase in daily precipitation intensity and an increase in the number of days with precipitation of varying intensity (more than 1 mm in the highlands, more than 10 mm in the low mountains). This leads to a shift in the spring onset to the earlier dates; dangerous floods in March have already been noted in the studied region.

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