ATLANTIS PRESS
Atlantis Highlights in Material Sciences and Technology (AHMST), volume 1
International Symposium "Engineering and Earth Sciences: Applied and Fundamental Research" (ISEES 2019)

Climate of the Caucasus Region of the Last 60 Years: Precipitation and Temperature Trends and Anomalies

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***Abstract* – Seasonal, annual trends of average, minimum and maximum temperatures, total precipitation and maximum daily precipitation from 1961 to 2017 in various climatic zones of the region have been studied in the paper. The study period was divided into two intervals from 1961 to 1975 and from 1976 to 2017. Since 1976, in all climatic zones of the Caucasus region, negative trends in average annual temperatures changed direction to positive ones. The strongest growth was observed in the summer season in all climatic zones. Changes in the seasonal and annual rainfall patterns are not so obvious: both an increase and a decrease in the amount of precipitation and daily maximums were observed. The paper presents a numerical assessment of the rate of degradation of glaciers in Terskol (high-mountainous zone) against the background of an increase in the rate of growth of summer temperatures in recent decades. Analysis of regional anomalies of mean monthly temperatures in 2017 showed that the record high value of mean monthly temperatures in the Caucasus region was in 2010.**

Keywords* – *Caucasus region; climatic zones; trends; anomalies; temperature; precipitation; glacier degradation.

I. Introduction

Climate is one of the most complex systems on Earth. The modern climate was formed in the quaternary period - the stage of the geological history of the Earth, which began 2.58 million years ago. It is characterized by the alternation of glacial and interglacial epochs; now the warm interglacial epoch, the Holocene, continues. Climate warming in the 20th century occurred unevenly over two periods: from 1910 to the 40-s of 20-th century and from 1976 to the present. By decision of the World Meteorological Organization (WMO), 1976 is considered the year when global warming began. From the data of instrumental measurements, it follows that during the past century the average temperature of the Earth rose by 0.74 ± 0.18

°C [1]. Each of the last three decades has been characterized by a higher temperature at the Earth's surface than any other decade since 1850. According to the third report of the Intergovernmental Panel on Climate Change (IPCC-2001), an increase in average annual global average surface temperature can reach 5.8 °C by 2100 compared to this time. According to the data of the 2nd Report of the IPCC (IPCC-1996), the corresponding estimate was only 3.5 °C. [2, 3].

The average growth rate of average annual air temperature in Russia since 1976 represent 0.46 °C/10 years (in the North Caucasus 0.47 °C/10 years). This is 2.5 times the growth rate of global temperature over the same period [4]. A WMO press release of March 22, 2018 notes a strong impact in 2017 on extreme weather events related to economic development, food security, health care, and migration. 2017 was among the three warmest years in the entire history of meteorological observations. Global temperatures in 2017 were 1.1 °C above pre-industrial levels (1750) [4].The fifth report of the IPCC for 2014 notes that "... the fact of climate warming is beyond doubt, and many of the observed events of the 1950s have no precedent for tens of thousands of years" [1].

The following definition of climate change was given in [5]: "Climate change means a statistically significant change in either the average climate state or its variability over a period of time (usually several decades or more)". Climate change for a given region or for the globe as a whole is characterized by the difference between some climatic variables for two given time intervals. The Summary for Politicians [6] notes that recent climate change and climate fluctuations are beginning to influence many other natural and anthropogenic systems. For example, settlements in mountainous regions are at increased risk of breakthrough floods of glacial waters caused by the melting of glaciers. The Climate Doctrine of the Russian Federation states that climate change is one of the most important international problems of the 21st century that go beyond the scientific problem [7]. Studies devoted to the problem of changing global and regional climate are carried out in many papers [8-11].

II. MATERIALS AND METHODS

Atmospheric regional phenomena undergo more significant changes and variations than global ones. The object of our study is the climate change of the part of the Caucasus region, located between 41°N - 44 °N and 41°E - 48 °E. The territory is represented by different climatic zones: plain (up to 500 meters above sea level (m a.s.l.), foothill (500 - 1000 m a.s.l.), mountain (1000 - 2000 m a.s.l.) and high -mountain (more 2000 m a.s.l.).

The aim of the study is to assess climate change in different climatic zones of the Caucasus over the past 56 years (1961-2017), especially in the modern period (from 1976, the onset of global warming), to identify the response of the degradation of the glaciers of the North Caucasus to changes in thermal regime, a comparative analysis regional and global temperature anomalies in 2017. In this work, annual and seasonal series of climate variables (temperature, precipitation) of three mountain weather stations: Akhty, Teberda, Terskol, foothill (Nalchik) and steppe (Prokhladnaya) stations were used on the site [13]. Information about the location of weather stations Akhty, Teberda, Terskol, Nalchik, Prokhladnaya are presented in Table 1.

TABLE 1. GEOGRAPHICAL LOCATION OF WEATHER STATIONS

Weather stations	Latitude, N	Longitude, E	Height above sea level, m a.s.l., zones
Akhty	41.28°	47.44°	1054 mountain
Teberda	43.45°	41.73°	1335 mountain
Terskol	43.15°	42.30°	2144 high- mountain
Nalchik	43.22°	43.24°	500 foothill
Prokhladnaya	43.46°	44.05°	198 plain (steppe)

Time series were investigated by methods of mathematical statistics and supplemented by linear trends calculated by the method of least squares. The angular coefficient of the linear trend equation (***b***) is a characteristic of the average rate of change of the climate variable at the considered time interval and is expressed in degrees per decade (°C/10 years, temperature) and in millimeters/month per decade (mm/10 years, precipitation). The strength of the trend was estimated by the parameter ***D*** (%) – the contribution of the trend to the variance explained. A statistically significant trend was estimated by the parameter *D* (%) > 8%. Along with the average seasonal air temperature, the seasonal (annual) index of maximum temperatures, obtained as the highest for the season (year) value of the absolute monthly maximum, and similarly the index of minimum temperatures, was considered. The changes in the absolute maxima and minima of temperatures for the weather station Terskol are given from 2006 to 2017 due to the lack of complete data series. 1961-1990 was used as the base period for the assessment of climatic norms, and the anomalies were calculated for each year as the difference between the value of the current value and the norm of the corresponding climate variable.

III. RESULTS AND DISCUSSIONS

Changes in annual and seasonal average temperatures (***T***), absolute minimums (***Min***), absolute maxima (***Max***) for two periods 1961-1975 and 1976-2017 for weather stations of different climatic zones are presented in Table 2 and in Figure 1. Since 1976, at all stations, negative trends in average annual and seasonal temperatures have changed directions to positive. Since 1976 the growth of annual temperatures is due to the growth of maximum temperatures, especially in the foothill (0.71 °C/10 years, *D* = 23%) and steppe (1.0 °C/10 years, *D* = 36%) zones. A negative trend with small rates occurred for minimum temperatures in two cases: the trend of winter minimum temperature in Nalchik (-0.1 °C/10 years, *D* = 0.1%) and Prokhladnaya (-0.02 °C/10 years, *D* = 0.02%) and average winter temperatures (-0.03 °C/10 years, *D* = 0%) in Terskol. But since their rates of change are insignificant and the contribution to the total variance is zero, it is possible to speak about the stability of these temperatures.

In the summer season 1976-2017 the greatest rise in average temperatures was observed at all stations (from 0.43 to 0.70 °C/10 years). The coefficients of determination are maximum (*D* = 38% - 50%), which demonstrates the functional linear growth of the summer temperature in all climatic zones, including the high-mountain. At high-mountain station Terskol the annual trend is positive due to the summer trend (0.43 °C/10 years, *D* = 38%); in winter, spring and autumn there were no temperature trends.

TABLE 2. CHARACTERISTICS OF THE LINEAR TREND B_1 (D_1) FOR 1961-1975 AND B_2 (D_2) FOR 1976-2017 OF THE AVERAGE TEMPERATURE OF THE CAUCASUS REGION

		Akhty		Teberda		Terskol		Nalchik		Prokhladnaya	
		b_1/b_2	D_1/D_2	b_1/b_2	D_1/D_2	b_1/b_2	D_1/D_2	b_1/b_2	D_1/D_2	b_1/b_2	D_1/D_2
Annual	*T*	**-0.6*/0.42**	**14/38****	**-0.6/0.37**	**13/33**	*-0.4/0.14*	*5/8****	**-0.61/0.54**	**11/49**	**-0.52/0.46**	**8/40**
	Min	-1.5/0.4	7/5	0.18/0.15	0/0	***-1.05***	***44***	**-4.37**/0.02	**18**/0	**-2.67**/0.12	**8**/0
	Max	0.2/0.45	0/5	-1.5/**0.5**	0/**8**	***0.63***	***30***	0.1/**0.7**	**1/23**	-0.27/**1.0**	7/**36**
Winter	*T*	**-2.2/0.4**	**19/10**	**-1.9**/0.31	**18**/5	**-1.8**/-0.03	**22**/0	**-1.77/0.46**	**14/13**	**-1.9/0.39**	**15/10**
	Min	**-2.75**/0.2	**16**/1	0.31/0.0	0/0	***-1.03***	***39***	**-5.07**/-0.1	**22**/0.1	-4.63/-0.02	18/0.02
	Max	**-1.7/0.65**	**10/10**	-0.07/**0.54**	2/**8**	***1.1***	***75***	**-2.69**/0.3	**14**/2	-4.65/0.59	36/5
Spring	*T*	**0.31/0.4**	**2/10**	-0.16/**0.26**	1/**12**	-0.2/0.09	1/1	-0.1/**0.51**	0.1/**29**	**0.09/0.4**	**0/21**
	Min	**-0.45/1.0**	**0/13**	0.0/**1.4**	0/**17**	***-1.04***	***54***	1.57/**1.3**	2/**18**	0.33/**0.98**	**0/10**
	Max	0.11/0.02	0/0	0.04/0.25	1/2	***0.55***	***38***	0.31/0.2	4/1	-1.45/0.49	6/7
Summer	*T*	0.07/**0.52**	0/**40**	0.06/**0.55**	0/**48**	-0.2/**0.43**	1/**38**	-0.07/**0.70**	0.1/**51**	0.05/**0.65**	**0/50**
	Min	0.24/0.07	0/0	**0.93/0.69**	**8/22**	***-0.53***	***51***	0.54/**0.62**	1/**13**	-0.64/**0.67**	1/**12**
	Max	0.07/0.26	0/2	**-1.4**/0.44	**8**/6	***0.63***	***30***	0.09/0.2	0.8/1	-0.27/**1.00**	0/**35**
Autumn	*T*	**0.11/0.38**	**0/10**	-0.03/**0.35**	0/**16**	**0.9**/0.04	**13**/0	-0.4/**0.5**	4/**20**	-0.34/**0.37**	3/**13**
	Min	-1.7/0.0	5/0	0.38/**1.07**	0/**11**	***-0.97***	***40***	-0.52/0.18	1/0	-0.73/0.27	1/1
	Max	**0.21**/0.13	**11**/0	-0.5/0.31	1/2	***0.66***	***37***	0.16/**0.2**	1/**13**	-0.41/**0.86**	1/**19**

** Negative variable trends are highlighted in grey*
*** Statistically significant trends are highlighted in bold*
**** The rate of change of the minimum and maximum temperatures in Terskol for 2006-2017 (°C/year) are highlighted in italic*

For the years 2006-2017 at the high-mountainous station Terskol, there was an increase in all seasonal and annual absolute maximums of temperatures, of which the most steady growth with a significant contribution to the total variance at the winter absolute maximums (b = 1.1 °C/ year, D = 75%). In the same period, there was a decrease in all seasonal and annual absolute minimum temperatures with the highest rate of decline in winter (b = -1.04 °C/year) and spring (b = -1.03 °C/year) absolute minimum temperatures.

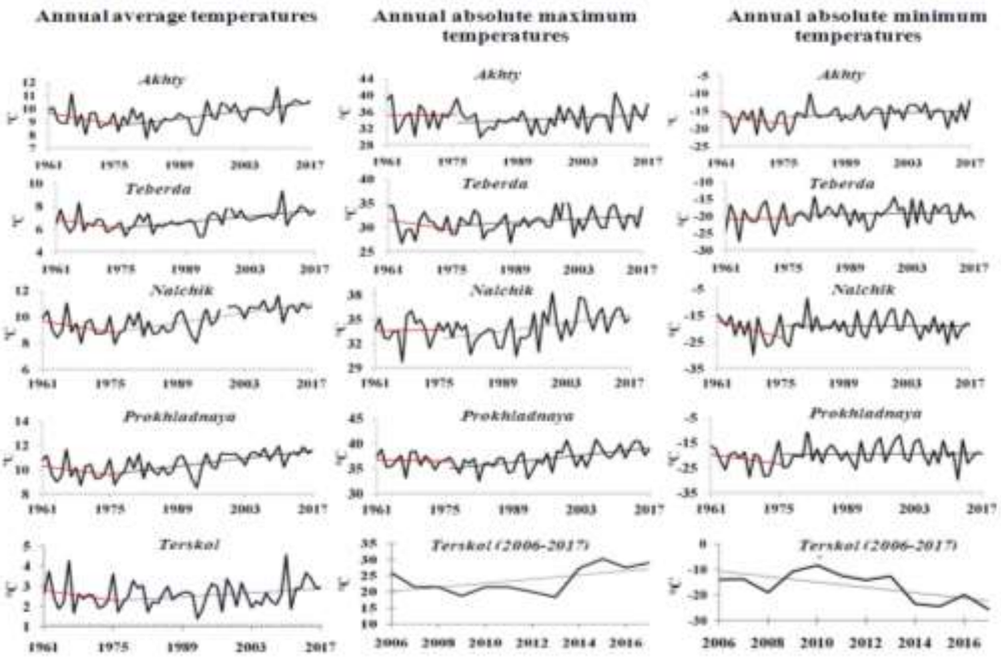


Fig. 1. The average, maximum and minimum annual temperatures with linear trends for 1961-1975 (red) and for 1976-2017 (black)

Table 3 presents the characteristics of the linear trend ***b*** (***D***) of the indicators of average annual and seasonal precipitation regime (***R*** is the total precipitation; ***Max*** is the maximum daily precipitation). The increases in the annual precipitation amounts at all weather stations of the Caucasus region are statistically insignificant. Positive and negative trends of precipitation totals and daily maxima were observed in two sub-periods at all stations. Since 1976 the positive trend of average annual precipitation amounts has changed direction in Akhty, Teberda, Terskol, Prokhladnaya; all trends are statistically insignificant.

TABLE 3. CHARACTERISTICS OF THE LINEAR TREND ***B₁*** (***D₁***) FOR 1961-1975. AND ***B₂*** (***D₂***) FOR 1976-2017 OF THE AVERAGE ANNUAL AND SEASONAL PRECIPITATION AT THE WEATHER STATIONS OF THE CAUCASUS REGION

		Akhty		**Teberda**		**Terskol**		**Nalchik**		**Prokhladnaya**	
		b₁/b₂	***D₁/D₂***	***b₁/b₂***	***D₁/D₂***	***b₁/b₂***	***D₁/D₂***	***b₁/b₂***	***D₁/D₂***	***b₁/b₂***	***D₁/D₂***
Annual	***R***	0.7/-1. 5	0/0	-32.2/17.7	2/3	-37/21.2	1/2	12.8/5.8	0/4	**-70.4**/7.5	**15**/1
	Max	-2.0/0.08	2/0	4.7/0.9	7/1	-	-	**9.24**/0.7	**13**/0	**9.7**/3.3	**10**/6
Winter	***R***	4.8/0.42	4/0	-25.8/-4.1	2/0	-23.9/-4.9	1/0	8.7/-0.32	4/0	0.42/3.35	0/4
	Max	0.05/0.53	0/1	1.0/-3.2	0/5	-	-	**5.0**/-0.16	**17**/0	2.35/0.6	6/4
Spring	***R***	11.2/-0.2	1/0	-18.4/**19.3**	4/**11**	-25.5/**19.4**	7/**8**	-31.5/3.3	5/0	**-43.05**/6.0	**15**/3
	Max	-0.6/0.6	0/1	0.7/0.8	0/0	-	-	-1.12/-1.14	0/2	-4.85/1.2	4/1
Summer	***R***	-22.6/-3.78	6/1	4.2/-2.68	/	-23/-2.58	2/0	6.41/-1.8	0/0	**-40.5**/-9.98	**12**/4
	Max	2.1/-0.22	2/0	2.8/-2.1	2/4	-	-	**8.12**/1.71	**16**/4	5.88/2.47	5/4
Autumn	***R***	9.6/1.97	2/1	26.5/2.23	2/0	53.2/7.7	6/1	**36.3**/4.74	**12**/1	**23.31**/9.0	**16**/6
	Max	-1.1/-0.84	0/1	2.8/1.1	1/1	-	-	**13.9**/-1.5	**13**/2	**16.62/3.5**	**31/11**

a. * *Negative variable trends are highlighted in grey*

b. ** *Statistically significant trends are highlighted in bold*

The increase in the average annual precipitation was observed due to the increase in the spring and autumn precipitation at the high-mountain station Terskol for 1976-2017. In the same period, the winter and summer sums of precipitation decreased slightly. All precipitation trends are positive, with the exception of summer precipitation amounts. The general trend for all stations is significant increase in autumn precipitation. In the current period, out of all trends in precipitation change, statistically significant trend occurred only at the steppe station Prokhladnaya for daily highs of autumn precipitation (3.5 mm/10 years, *D* = 11%).

An important task for the region is to assess the reaction of the mountain ecosystem during global warming, study the mechanisms of glacier degradation. As mentioned above, over the entire period of research from 1961 to 2017, the annual, spring and autumn temperatures at the station decreased at a low speed. From the onset of global warming, the growth rate of average summer temperatures increased significantly to 0.43 °C/10 (*D* = 38%).

The authors of [13] analyze the environmental aspects of natural and climatic changes in the Elbrus region (North Caucasus), leading to the processes of glacier degradation. Using data from satellite images and aerial photographs in [14], the authors describe the rate of degradation of the Caucasus glaciers (Maly Azau, Garabashi and Terskol.) Using data from the area of glacier reduction, we will conduct a numerical assessment of the rate of degradation.

According to the results of the correlation analysis, with a high significance level Sig <0.05 (at 95% confidence interval) the rate of change of the total area of the Terskol glacier has statistically significant correlation coefficients (R = 0.93) with average summer temperatures at station Terskol. The task of identifying the influence of the thermal regime on the degradation of the glacier is solved by the method of simple linear regression. The regression equation for the dependence of the retreat rate of the total area of the Terskol glacier on the average summer temperature of Terskol:

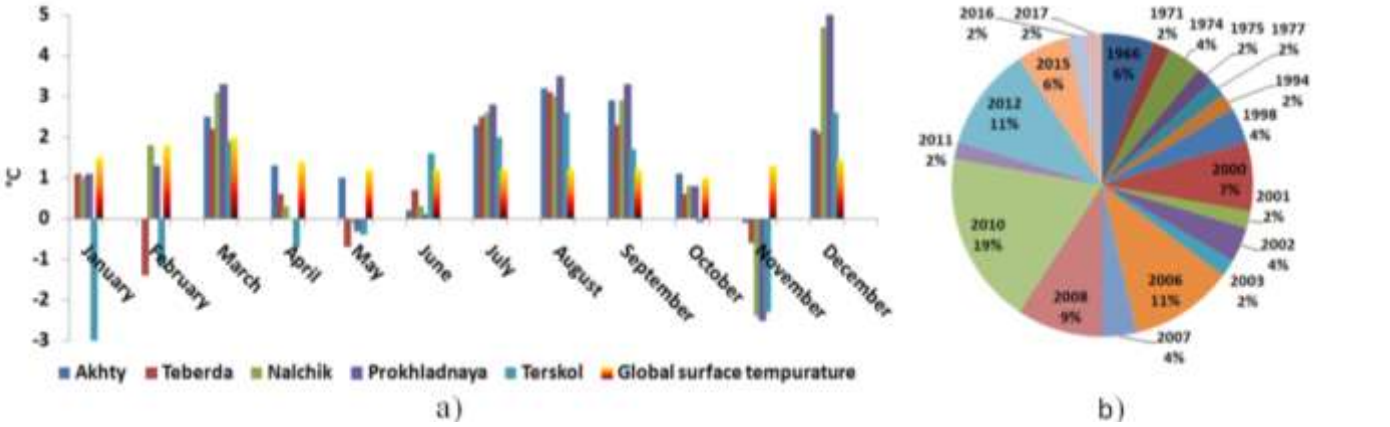
$$V_S = 13.25(\pm\delta_t)t_{VI-VIII} - 141.56(\pm\delta),$$

where V_S is the rate of change in the total area of the Terskol glacier for 1961-2015; $t_{VI-VIII}$ is the average summer temperature(July August) for 1957-2015; δ_t is the standard error of the predictor slope factor $t_{VI-VIII}$, δ is the standard error of the constant.

The coefficient of determination R^2 = 0.864, that is, describes 86.4% of the initial data and indicates a high accuracy of the regression model. From the regression equation, it follows that at 95% confidence interval an increase in the average summer temperature by 1 °C will result in an increase in the retreat of the Terskol glacier area from 8.95 thousand m^2 to 17.55 thousand m^2 (13.25 ± 2 δ_t), which can lead to a significant imbalance of the mountainous ecosystem.

We will make a small comparison of the anomalies of average monthly temperatures of 2017 (data from stations of the North Caucasus) with anomalies of average monthly global temperatures on the Earth's (land) territory in 2017. Global data were obtained from the website of the National Centers for Environmental Information (NCEI) and the ocean and atmosphere studies (NOAA) [15]. Global temperature exceedances over the whole Earth's land area are calculated as the difference between the global temperature of each month of 2017 and the average temperature of each month in the 20th century. Temperature anomalies in the stations of the Caucasus region were calculated as deviations of average monthly values in 2017 from climatic norms for 1961-1990.

Figure 2 shows the histograms of global temperature exceedances by months in 2017 over temperatures in the 20th century and anomalies of average monthly temperatures in 2017 according to stations of the Caucasus region. In 2017, in the Caucasus region, there were positive anomalies of mean monthly temperatures, except for November, when all stations recorded temperatures below the climatic norm. At the high-mountain station Terskol (2144 m a.s.l.), negative anomalies occurred in January, February, April and May. In general, for all stations, the average annual temperature anomaly was 1.23 °C. According to data from the site [15], the globally averaged temperature of the Earth's surface in 2017 was 1.31 °C above the average value of the 20th century, which is comparable with the results obtained in the Caucasus region. 2017 was the third year with the highest temperatures in all years from 1880–2017, after 2016 (the warmest) and 2015 (the second warmest).



a) anomalies of average monthly temperatures in 2017; b) frequency of years (%), which account for the maximum values of average monthly temperatures for 1961-2017.

Fig. 2. Comparative analysis of regional and global surface air temperatures

According to the analysis, 2010 was still a record in the study Caucasus region, in contrast to the global temperatures of the Earth's territory (land), where the record high average monthly temperatures were in 2016 (2017 is the third place). In 2010, 19% of the highest monthly average temperatures for the period 1961-2017 were accounted for; followed by the year in descending order: 2006 and 2012 (11% each), 2008 (9%), 2000. (7%), etc. The number of record high average monthly temperatures for 2017 is 2% (Fig.2b).

IV. Conclusion

1. In all climatic zones of the Caucasus region negative trends in average annual temperatures changed their direction to positive ones since 1976. In the summer season 1976-2017 the greatest rise in average temperatures was observed at a rate from 0.43 to 0.70 °C/10 years (D =38% - 50%) in all climatic zones.

2. Both positive and negative tendencies were observed in the amounts of precipitation and daily maxima in all climatic zones in both sub-periods. The increase and decrease in annual precipitation are statistically insignificant in all climatic zones with the exception of autumn precipitation in the steppe zone.

3. The cause of the degradation of the studied glaciers is significant positive anomalies of summer temperatures. In the 21st century, there is increase in the rate of degradation of glaciers against the background of statistically significant increase in summer temperatures from 1976 to the present period.

4. The first two decades of the 21st century are the record for high levels of both global and regional temperatures, and 2010 remains the record year for anomalously high temperatures in the Caucasus region.

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