Analysis of climate change in Terskol over the last 60 years

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Abstract: In connection with the ongoing climatic changes, the tasks of monitoring the climate of the high-mountainous zone of the Caucasus are of particular importance. Climatological studies in this work are based on the material of long-term meteorological observations from 1961 to 2020, according to the Terskol weather station. Correlation analysis showed the spatial homogeneity of temperature changes in Terskol and weather stations of all climatic zones of southern Russia, in contrast to the regional precipitation regime with a small scale of coherence (up to 200 km). In the modern period (1991-2020), the change in average temperatures in comparison with climatic norms (1961-1990) is not confirmed by statistical estimates, with the exception of the summer season. Over the 60-year period, from 1961 to 2020, there was a statistically significant increase in average summer temperatures by 0.31 °C/10 years (D = 26.8%). At the turn of the 20th and 21st centuries a steady increase in winter, spring and annual temperatures is formed, while summer temperatures maintain a positive trend, but statistically insignificant at this time interval. Period from 2006 characterized by the addition of a statistically significant increase in the absolute maximums of all seasonal temperatures, in contrast to the sums and daily maximum precipitation, the decrease in which in the winter season is statistically insignificant, and there are no trends in other seasons. Such a prevailing thermal and precipitation regime in recent decades has become the main component of many factors leading to dangerous slope phenomena, glacier degradation and significant changes in the hydrological regime.

1. Introduction
The problem of studying global and regional climate change is one of the priorities facing the environmental and economic aspects of sustainable development of society [1, 2]. In modern times, in connection with the ongoing climatic changes, the tasks of monitoring the climate of the high-mountainous zone of the Caucasus are of particular importance. Melting snow and ice, retreating and disappearing glaciers lead to changes in landscapes, the formation of new lakes and the activation of destructive natural phenomena. All these processes ultimately have a serious impact on economic activity. At the same time, the importance of glacial runoff as a resource of water supply in mountainous, foothill and lowland zones in the south of the European territory of Russia (ETR) is growing [3].

2. Materials and research methods
The climatological studies in this work are based on the material of long-term (1961-2020) observations of the Terskol weather station (w/station) provided by the North Caucasian Directorate of the Hydrometeorological Service (NC DHMS). Terskol is a high-mountain w/station located in the Elbrus region (43°15′ N, 42°30′ E) between the slope of Cheget Mountain and the Terskol Gorge at an
altitude of 2144 m above sea level (m a.s.l.). The work considered the averaged values of annual and seasonal temperatures (average, maximum, minimum) and precipitation (total precipitation, daily maximum precipitation) for calendar seasons and the year as a whole. Average annual values refer to the time interval from January to December of the year in question. The summer season includes June-August, the winter season includes December of the previous year, January, February. Anomalies were calculated as deviations from the 1961-1990 mean. To analyze the spatial correlation of temperature and precipitation of Terskol with other w/stations, data from 19 w/stations were used, representing all climatic zones of southern Russia. The estimation of the coefficients of linear trends was obtained by the least squares method and expressed in °C/10 years or in mm/month/10 years. Checking the significance of the regression model (the significance of the coefficient of determination $R^2$) is carried out using the Fisher criterion ($F$-test), the calculated value of which is found as the ratio of the variance of the initial series of observations of the studied indicator and the unbiased estimate of the variance of the residual sequence for this model. A null hypothesis is put forward that the equation as a whole is statistically insignificant: $H_0: R^2 = 0$ at the significance level $p = 0.05$. To test the hypothesis about the significance of the coefficient of determination (trend), the factual $F$-test is calculated:

$$F = \frac{R^2}{1-R^2} \cdot \frac{n-k-1}{k},$$  \hspace{1cm} (1)

where $R^2$ is the coefficient of determination (or the contribution of the trend to the explained variance $D = R^2 \cdot 100\%$), $n$ is the number of observations, $k$ is the number of independent linear regression parameters, $df$ is the number of degrees of freedom determined using the expression $df = n-k-1$. The factual value of the Fisher criterion ($F_{\text{act.}}$) is calculated as the ratio of the variance of the regression to the variance of the residuals, calculated per one degree of freedom by formula (1). The theoretical value of the Fisher criterion ($F_{\text{thor.}}$) is determined from tables at a given significance level $p = 0.05$ and the number of degrees of freedom $df$ [4]. If the factual value of the Fisher criterion is higher than the theoretical one ($F_{\text{act.}} > F_{\text{thor.}}$), then the trend is statistically significant.

### 3. Results and discussion

To describe the general spatial regularities of temperature and precipitation, the spatial structures of precipitation temperature fields were obtained and analyzed from the data of Terskol and 19 w/stations of different climatic zones of south of the European territory of Russia (ETR), and spatial correlations between them were determined depending on the scale of the distance between the stations [5]. Figure 1a shows that in all climatic zones of the region, changes in annual and seasonal average temperatures are synchronous in time, including for the high-altitude w/station Terskol, at which there is only a lag behind other climatic zones in the growth of peak values of positive anomalies. In figure 1a, in seasonal temperatures, the temperatures of Sochi are highlighted in red, the temperatures of Terskol are highlighted in black, the other 18 w/stations of all climatic zones are blue. Changes in the regime of annual precipitation (as well as seasonal) in different climatic zones, in contrast to the temperature regime, are not synchronous (figure 1b). To carry out a correlation analysis between the temperature /precipitation station Terskol and 19 stations in the southern Russia, we denote $x_i (j)$ - mean annual air temperatures or the amount of precipitation at any w/station $i$, where $j = 1, \ldots, N_i$, $j$ - year, $N_i$ is the total number of measurements. Similar measurements at another station, $l$, respectively $x_l (k)$, where $l = 1, \ldots, N_l$, $i$ is the year, $N_l$ is the total number of measurements. It is necessary that $N_l = N_k$ for joint analysis. The distance ($L$) between w/stations is calculated based on the geographical coordinates (latitude $\varphi$; longitude $\lambda$) of each of the pairs of stations according to the formula:

$$L = \text{arcos} (\text{sin} \varphi_1 \cdot \text{sin} \varphi_2 + \text{cos} \varphi_1 \cdot \text{cos} \varphi_2) \cdot \text{cos} \varphi_2 \cdot \text{cos} \Delta \lambda.)$$ \hspace{1cm} (2)

The linear relationship between the series $x_i (j)$ and $x_l (k)$ was quantified by the Pearson correlation coefficient $r_{kl}$.
where $\bar{x}$ and $\bar{y}$ are the average values of the variables $x$ and $y$, respectively; $\sigma_x$ and $\sigma_y$ are standard deviations of variables $x$ and $y$; $n$ - number of observations. If the significance level ($\text{Sig.}$) of the correlation does not exceed 0.05 ($p < 0.05$), this means that the correlation is random with a probability of no more than 5%.

![Graphs showing seasonal temperatures and annual precipitation](image)

**Figure 1.** Annual variation of the average seasonal (a) and annual temperature (b) and the amount of precipitation (b) according to 20 w/stations of different climatic zones of southern Russia.

This usually becomes the basis for concluding that the correlation is statistically significant. Otherwise ($p > 0.05$) the relationship is recognized as statistically unreliable and is not subject to meaningful interpretation [4]. After calculating all possible combinations of $r_{ik}$, the obtained data were
used in the form of lines $A_r$, presented as a sequence of numerical values of the correlation coefficients between temperatures ($c = T$) or precipitation ($c = P$) (tables 1 and 2).

**Table 1.** Correlations of temperatures $A_T$ between Terskol and stations in the south of the ETR(1-20)*.

|   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $r_t$ | 20  | 0.8 | 0.6 | 0.6 | 0.5 | 0.6 | 0.7 | 0.6 | 0.8 | 0.7 | 0.6 | 0.6 | 0.6 | 0.8 | 0.7 | 0.8 | 0.7 | 1.0 |

**Table 2.** Correlations of precipitation $A_P$ between Terskol and stations in the south of the ETR(1-20) *.

|   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $r_p$ | 20  | 0.2 | 0.1 | 0.1 | -0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.4 | 0.1 | 0.1 | -0.1 | 0.2 | 0.1 | 0.4 | 0.3 | 0.8 | 0.3 | 0.1 | 0.1 |

* where numbering n = 1,2,3… .20 correspond to stations:

1. Acht 6. Izobilny 11. Makhachkala 16. Sochi
2. Buynaksk 7. Kizlyar 12. Mozdok 17. Stavropol
3. Vladikavkaz 8. Kislovodsk 13. Nalchik 18. Teberda
4. Derbent 9. Krasnodar 14. Prokhladnaya 19. Cherkessk
5. Izberg 10. Maykop 15. Rostov-on-Don 20. Terskol

Scatter diagrams of correlation matrices of air temperature and precipitation in the studied region are shown in figure 2. Each of the matrix elements is shown depending on the distance of stations from each other, specified in the distance matrices. From a comparison of figures 2a and 2b, it follows that there is a significant difference in the correlation structure of the fields.

Figure 2b shows that the spatial correlation of precipitation for all climatic zones tends to zero at distance scales of about 600 km and takes negative values «Terskol – Derbent» and «Terskol – Nalchik». If we set the threshold correlation value $R = 0.5$, then it can be seen that the correlation of precipitation decreases from the maximum with Teberda (mountainous zone, 1280 m a.s.l.) $r_p = 0.81$ to $r_p = 0.4$ to -0.1 for all climatic zones and takes negative values for the pairs «Terskol – Derbent» ($r_p = -0.07$) and «Terskol – Nalchik» ($r_p = -0.05$). All correlations, with the exception of «Terskol-Teberda», are insignificant (Sig. > 0.05).

![Scatter diagrams](image1.png)

**Figure 2.** Diagrams of the scattering of the values of the correlation of temperatures (a) and precipitation (b) between the pairs of «Terskol – w/stations» of different climatic zones of the southern Russia.
Figure 2a shows that the correlation of temperatures of different w/stations is quite high and, on the scale of distances from 0 to 600 km, falls mainly within a narrow range from \( r_t = 0.83 \) (Teberda) to \( r_t = 0.6 \) for mountainous, foothill and plane zones. The minimum correlation between the temperature of Terskol and other w/stations was determined for two pairs of w/stations: «Terskol – Rostov-on-Don» \((r_t = 0.554)\) and «Terskol – Derbent» \((r_t = 0.485)\), located at the greatest distance from Terskol.

The correlation between the precipitation of Terskol and w/stations decays rather quickly with the distance between them and with a decrease in the altitude above sea level. The obtained estimates of the spatial distribution indicate that the correlation structure of the Terskol precipitation fields has a small correlation scale, both horizontal (km) and vertical-zonal (m, altitude). Temperature fields are characterized by a higher degree of horizontal spatial coherence (i.e., a larger correlation scale) than precipitation fields. The formation of the temperature regime depends more on large-scale atmospheric circulation, and a significant role in the formation of precipitation fields, in addition to the features of large-scale circulation, is played by regional factors (underlying surface, complex orography of mountain ranges and massifs, vertical zoning, etc.).

Using the methods of mathematical statistics, results were obtained that characterize changes in temperature and precipitation over the past 60 years: averaged temperatures and precipitation for 1961-2020, climatic norms (1961-1990, base period), averaged values in the modern period 1991-2020, the results of the \( t \)-test for determining the statistical equality/inequality of the means in the base and modern periods, as well as characteristics of the distribution (Kolmogorov-Smirnov (KS) test), extreme values, the rate of meteorological parameters change taking into account \( F \)-test. Statistics of changes in seasonal and annual temperatures and precipitation are presented in table 3 and are divided into four blocks:

I. Assessment of the statistical difference of averages in the base and modern periods;
II. Characteristics of the form of distribution of meteorological parameters for the entire period;
III. The number of extremes of average temperatures above / below the threshold value;
IV. Regression characteristics (slope of regression, trend contribution to the explained regression, \( F \)-test) for the entire period. Statistical analysis was carried out using software SPSS version 21 (IBM Inc.) [6].

Comparative analysis of Terskol average temperatures in the base period 1961-1990 and modern period 1991-2020 (table 3, \( m=3, 4 \) ) showed that in the modern period the average summer temperatures \( t = 12^\circ C \) statistically significantly exceeded the climatic norm \( N = 11^\circ C \) (Sig. = 0.05). The average values of other seasonal and annual temperatures are statistically equal to their climatic norms.

Table 3. Summary characteristics of temperature (a) and precipitation (b) changes according to data from the Terskol, 1961-2020.

|   | Statistics, 1961-2020 | Winter | Spring | Summer | Autumn | Annual |
|---|----------------------|--------|--------|--------|--------|--------|
| 1 | Average \( \bar{\mu} \) (st. deviation),\(^\circ\)C | -6.5(1.6) | 1.9(0.9) | 11.5(0.86) | 3.7(1.0) | 2.6(0.7) |
| 2 | Confidence interval * | [-9.7 - 3.3] | [0.0 - 3.6] | [9.7 - 13.3] | [1.7 - 5.7] | [1.2 - 4.0] |
| 3 | \( N_{1961-1990} \) / \( \bar{\mu} \) 1991-2020, \(^\circ\)C | -6.4/-5.6 | 1.8/1.9 | 11.0/12.0 | 3.8/3.6 | 2.54/2.7 |
| 4 | **t-test, Sig. < 0.05** | 0.42 | 0.72 | 0.00 | 0.30 | 0.16 |
| N1961-1990 / \( \bar{\mu} \) 1991-2020 not equal | | | |
| II.5 | Range \( R \), \(^\circ\)C | 8.8 | 4.6 | 4.1 | 6.4 | 3.1 |
| 6 | Test KS (\( p=0.05, \)Sig. > 0.05) norm. distribution | 0.96 | 0.96 | 0.96 | 0.72 | 0.41 |
| III. | Number of extrema, \( n \) | 1≤ -11.5\(^\circ\)C | 1≤ 4.5\(^\circ\)C | 0 | 1≤ 7.2\(^\circ\)C | 3≤ 4.3\(^\circ\)C |
| 7 | | | 1≤ 0.8\(^\circ\)C | | |
From the mid-90s to the present, positive anomalies prevail in summer temperatures, the maximum of them (+ 2.5°C) were observed in 2006 and 2010, which was caused by the predominance of anticyclonic weather at that time. Such an anomaly exceeded the interannual variability of summer temperature (σ = 0.86 °C) by more than three times, which is realized with the probability p = 0.13% of the occurrence of the event. In 2020 there was an excess of temperatures in summer by Δt = ± 1.1°C (σ = 0.9°C), which slightly exceeded the interannual variability. The winter season of 2020 was distinguished by the highest value of the temperature anomaly over the past 60 years, Δt = ± 2.8 °C. For the period from 1961 to 2020 in the spring season of 2018 one value of the average air temperature (4.5 °C) was identified, which was classified as extremely high. In winter seasons, at a climatic norm of an average temperature N = -6.4 °C, one extreme above the threshold (t ≥ -2.7 °C) in 1966 (base period) and one extreme below the threshold (t ≤ -11.5 °C) in 2008 (modern period) were revealed. In autumn seasons with a climatic norm N = + 3.8 °C: one extreme below the threshold (t ≤ -0.8°C) in 2011 and one extreme above the threshold (t ≥ 7.23 °C) in 1975. In summer seasons there were no average temperature extremes. In contrast to the winter, spring and autumn seasons, in the summer seasons 1961-2020 the growth rate of average summer temperatures during this period was a high value of 0.31 °C/10 years (D = 37%, figure 3a), being statistically significant at the 5% level.

In the last twenty years (2000-2020), characterized by intense melting of the glaciers of the Central Caucasus, the rate of growth of the annual temperature increased to 0.68 °C/10 years (D = ± 32%, $F_{\text{theor.}} = 8.97$ for $d_f = 4$, which determines the trend of average annual temperatures as statistically significant). It is interesting to note that the contribution to the increase in the average annual temperature in 2000-2020 also introduced significant trends in winter (1.4 °C/10 years, $D = 19.3\%$) and spring temperatures (0.9 °C/10 years, $D = 26.8\%$). The growth rate of average summer temperatures is still positive, but at this time interval is insignificant (0.4 °C/10 years, $D = 11.1\%$), as well as the rate of autumn temperatures (0.2 °C/10 years, $D = 1.4\%$).

### Table 3

| IV.  | Slope linear trend, $a$, °C/10 years | 3   | 4   | 5   | 6   | 7   |
|------|-------------------------------------|-----|-----|-----|-----|-----|
| 8    | -0.02                               | 0.08| **0.31** | 0.01| 0.1 |
| 9    | Determination coefficient, $D(\%)^{***}$ | 0.1 | 1.5 | **36.8** | 0.0 | 6.0 |

### Table 3—continuation

| I.   | Average, $\bar{X}$, (st. dvt.), mm | 2   | 3   | 4   | 5   | 6   | 7   |
|------|-----------------------------------|-----|-----|-----|-----|-----|-----|
| 10   |                                   | 158.4 (85) | 253.6 (77) | 299.6 (65) | 252.6 (93) | 964.4 (16) |
| 11   | Confidence interval *              | [329 ± 0] | [408 ± 100] | [429 ± 170] | [439 ± 66] | [1296 ± 63] |
| 12   | $N_{1961-1990} / \bar{X}_{1991-2020}$, mm | 158/158.7 | **237.6/270** | 302.3/296.8 | 236/269 | 936/993 |
| 13   | **$t$-test, $S_i\geq 0.05$**      | 0.95 | 0.049 | 0.63 | 0.056 | 0.068 |
|      | $N_{1961-1990} / \bar{X}_{1991-2020}$ not equal | | | | | |

| II.  | Range $R$, mm                      | 14  | 15  | 16  |
|------|-----------------------------------|-----|-----|-----|
| 14   |                                   | 425.5 | 373.4 | 392.3 | 439.0 | 729.1 |
| 15   | Test KS ($p=0.05$)/$S_i<0.05$ norm. | 0.913 | 0.660 | 0.686 | 0.967 | 0.999 |

| III. | Number of extrema, $n$             | 16  |
|------|-----------------------------------|-----|
| 16   |                                   | 2 ≥ 445 | 2 ≥ 426 mm | 1 ≤ 141 mm | 1 ≥ 533 mm | 3 ≥ 470 mm | 1 ≥ 1425 mm |

* Lower and upper boundaries of $t_w$, ± 2σ at 95% confidence interval, σ - standard deviation;
** Cells with a statistically significant difference in the mean of the two periods are highlighted: yellow - average (1991-2020) > N (1961-1990), blue - average (1991-2020) < N (1961-1990);
*** Significant trend coefficients (D > 6.5%) are marked in bold.
Figure 3. Summer (a) average temperatures with a trend for 1961-2020 (5-year moving) and (b) winter absolute temperature maximums with a trend of 2006-2020, Terskol.

According to our data, over the past fifteen years (2006-2020) there has been a statistically significant increase in the absolute maximums of all seasonal temperatures: winter by 0.83 °C/year ($D = 70\%$) (Figure 3b); spring by 0.65 °C/year ($D = 62\%$); summer by 0.52 °C/year ($D = 28\%$); autumn by 0.59 °C/year ($D = 44\%$). Despite the short time series (15 years), the actual value of $F_{\text{fact}} = 6.4$, calculated for $n = 15$ ($df = 13$), exceeded $F_{\text{theor}} = 4.67$, which confirms the statistical significance of the trend of absolute temperature maximums in 2006-2020.

Thus, over a long 60-year period at the high-altitude w/station Terskol, there was a statistically significant increase in mean summer temperatures (0.31 °C/10 years, $D = 36.8\%$), while over 100 years (0.001 °C/year) according to [7], and for 60 years (0.008 °C/year) [8], there was an almost stable annual temperature regime and a statistically insignificant trend ($D = 4\%$ at a 5% level) due to the absence the trend of other seasonal temperatures.

Weather station Terskol like any other high-mountain w/station is characterized by a fairly high amount of precipitation during the year. The value of the average annual precipitation rate (1961-1990) in Terskol is 935.9 mm, with the greatest amount of precipitation falling in the summer season (302.3 mm), the least in the winter season (158.0 mm). Precipitation trends are statistically insignificant and vary depending on the rainy season and the length of the time series under study. If in work [7] the trend of precipitation amounts in the cold season (October-April 1951-2013) showed their steady increase at a rate of 30.3 mm/10 years ($D = 13\%$), then according to our data in the period 1961-2020 the growth rate decreased to statistically insignificant ($a = 15.41 \text{ mm/month/year}, D=3.2\%$), which took place due to a sharp decrease in the amount of precipitation in the 2006-2020 seasons (Figure 4a). From Table 3 ($nn = 10, 11$) it can be seen that at the 5% level ($t$-test) a significant excess of precipitation amounts (270 mm, $\text{Sig.} = 0.049$) over the climatic norm (237.6 mm) took place in spring seasons of the modern period and at the border of significance ($\text{Sig.} = 0.056$) in the autumn season (236 mm/269 mm). Extreme amounts of precipitation exceeding the upper threshold were determined for all seasons (Table 3, $nn.13$), and precipitation extremes were both above the threshold ($1 \geq 533 \text{ mm, 1998}$) and below the threshold ($\leq 141 \text{ mm, 1967}$) took place during the summer seasons.

Figure 4a shows that the general trend over the past 60 years has a slightly negative direction, with the 5-year moving average showing periods of increase and decrease in winter precipitation of approximately the same duration until the mid-90s of the 20th century. Since the beginning of the 2000s there was a decrease in winter precipitation amounts, continuing in the present period.

Figure 4b shows that the winter daily maximum precipitation in 2006-2020 had a pronounced negative trend with the largest explained variance ($a = -0.98 \text{ mm/month/year}, D = 15\%$) compared to seasonal maximum precipitation (spring: $a=0.31 \text{ mm/month/year}, D=1\%$; summer: $a=0.26 \text{ mm/month/year}, D = 2\%$; autumn: $a = 0.3 \text{ mm/month/year}, D = 0.4\%$). The actual value of the $F$-criterion for the winter trend was $F_{\text{fact}} = 2.26 < F_{\text{theor}} = 4.67$, which did not confirm the significance of the negative trend of the winter maximum daily precipitation, as well as other seasonal trends.
Figure 4. The amount of precipitation in a) winter season (December - February) with trends for 1961-2020 and b) maximum daily winter precipitation with a trend 2006-2020, Terskol.

4. Conclusion
Since the beginning of the 21st century, there has been a change in the thermal regime of Terskol: stable annual, winter, spring and autumn average temperatures in the 20th century accelerated their growth to statistically significant trends, while summer temperatures retained a positive trend, but the trend is no longer statistically significant. Period from 2006 characterized by the fact that a statistically significant increase in the absolute maximums of all seasonal temperatures was added to a significant increase in average temperatures, in contrast to the sums and daily maximums of precipitation, the decrease in which in the winter season is statistically insignificant, and there are no trends in other seasons. Such a prevailing thermal regime and precipitation regime in recent decades has become the main component of many factors leading to a reduction in the area of glaciers in the Central Caucasus and a significant change in the hydrological regime.

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