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Precipitation Dynamics and Dangerous Phenomena in the Eastern Caucasus

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The increasing development of mountainous areas and the growth of tourism and economic activities have led to a rise in the number of facilities exposed to natural hazards. Climate change is altering the activity of hazardous natural processes in mountainous regions. Atmospheric precipitation plays a key role in triggering hydrological hazards in complex terrains. This study addresses the detection of statistically significant changes in precipitation patterns at the regional level and their correlation with the annual cycle of hazardous hydrometeorological processes that threaten infrastructure and populations in the Eastern Caucasus. Historical data from meteorological stations located in the mountainous zones of the Republic of Dagestan and the Chechen Republic were used as primary sources. Time series of various precipitation characteristics (annual, seasonal, monthly, and daily) were compiled, covering the period of most intense warming from 1976 to 2023. Mathematical statistics and big data processing methods were applied to identify statistically significant trends in atmospheric precipitation. The results indicate that common regional trends in precipitation patterns across the Eastern Caucasus include an increase in various precipitation characteristics in March and a decrease in August. Comparing these trends with the annual distribution of hazardous hydrometeorological events suggests that the mountainous part of the region will likely continue to experience a decline in precipitation characteristics during the high flood and mudflow season. At the same time, high-altitude areas may see an increase in rainfall-induced hydrological hazards in July, linked to the observed trend of more frequent high-intensity precipitation days.

Keywords: Climate change, precipitation, Eastern Caucasus, Republic of Dagestan, Chechen Republic, nonparametric methods of mathematical statistics, natural hazards of a hydrometeorological nature.

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1. Introduction

Investigating how changes in precipitation patterns contribute to hydrometeorological hazards in mountain regions continues to be a pressing research objective. This is driven by the increasing development of mountain territories, alongside the expansion of tourism infrastructure and economic activity. Under conditions of local climate change in mountain areas, the frequency and other characteristics of hazardous natural processes typical of regions with complex terrain are changing.

Atmospheric precipitation plays a key role in initiating hydrological hazards in mountainous terrain. Consequently, a significant body of work is devoted to studying contemporary changes in their patterns and its influence on hazardous natural processes [*Korchagina*, 2024; *Kundzewicz et al.*, 2013; *Tabari*, 2020; *Trenberth*, 2011].

Studies by authors [*Martel et al.*, 2018; *Zhang and Delworth*, 2018] have shown that for identifying climate trends, regional studies are preferable to local ones, as the latter are subject to a higher degree of natural climate variability. Such studies conducted for the North Caucasus are presented in [*Korchagina*, 2021; *Tashilova et al.*, 2022].

The presence of long-term trends in regional climate characteristic series suggests that sustained changes and their direction are likely to persist. According to the authors of [*Şen*, 2012], the influence of a period of sustained changes on the activity of hydrometeorological natural hazards depends on its duration.

This study aims to identify climatically induced changes in precipitation patterns in the Eastern Caucasus from 1976 to 2023 and to compare the identified changes with the annual cycle of hazardous hydrometeorological processes that that endanger the region's infrastructure and population.

2. Materials and Methods

The changes in the average and maximum per month daily precipitation, monthly totals, average per season monthly precipitation (hereinafter referred to as average seasonal), and average per year monthly totals (hereinafter referred to as average annual) of atmospheric precipitation over the territory of the Republic of Dagestan and the Chechen Republic were investigated using historical series of meteorological measurements from specialized datasets provided by the Federal State Budgetary Institution All-Russian Research Institute of Hydrometeorological Information – World Data Center (hereinafter referred to as RIHMI-WDC) [*Bulygina et al.*, 2024].

Precipitation regime characteristics are calculated based on the processing of daily data from meteorological stations. For each of the stations located in the mountainous zone of the Republic of Dagestan (Sulak Vysokogornaya, and Akhty) and on the territory of the Chechen Republic (Grozny and Gudermes), the following time series were compiled for the period from 1976 to 2023: 12 series of monthly precipitation totals; 5 series of average seasonal and average seasonal annual; 5 series of the number of days per month with precipitation exceeding 1 mm, 5 mm, 10 mm, 15 mm, and 20 mm; and two series on average daily precipitation (hereinafter referred to as daily average) and daily maximum precipitation for the month.

The choice of a linear trend model for investigating long-term climate change trends is justified by its informativeness and the well-developed mathematical apparatus behind it [*Blöschl et al.*, 2019; *Korchagina*, 2022]. A set of both parametric and non-parametric methods of mathematical statistics was used to determine the presence of trends, their estimates, and statistical significance [*Ali et al.*, 2019; *Panda and Sahu*, 2019]. The employed approaches and methods are described in more detail in [*Korchagina*, 2024].

In conclusion, the information on hazardous events that caused material damage to the economies of the regions, as presented in the updatable database [*Shamin et al.*, 2019], was analyzed.

3. Results and Discussion

3.1. Mountain zone of the Dagestan Republic

The statistical characteristics of the constructed time series allow for the assessment of the presence of outliers, their quantity, and their significance for selecting the method of building a linear trend model. The diagrams in Figure 1 illustrate the average monthly precipitation based on data from the Republic of Dagestan meteorological stations for the period 1976–2023. In the high-mountain region, outliers are either absent or constitute less than 10 percent in all months except for August. In August, the percentage of outliers is 12.5%.

Furthermore, the presence of downward outliers in April, May, and August is noteworthy. In a study conducted for a longer period (1961–2023) [*Korchagina*, 2024], such an outlier was found only in May. At lower altitudes, according to data from the Akhty meteorological station (Figure 1, bottom), the maximum percentage of outliers is 8.33 and occurs

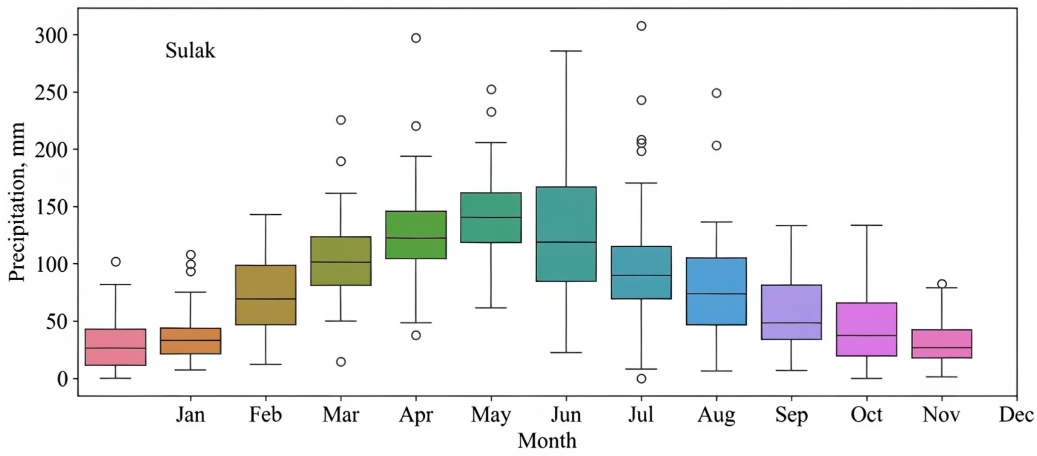

Figure 1. Statistical characteristics of the time series (1976–2023) of monthly precipitation according to data from the Sulak Vysokogornaya (top) and Akhty (bottom) meteorological stations.

in May, as in the high-mountain area. Tests of data for conformity to a normal probability distribution show that from April to October and in December, the series are normally distributed. A different situation is observed in the high-mountain area, according to data from the Sulak Vysokogornaya meteorological station. Here, the time series of monthly precipitation totals in March, April, June, July, and from October to December adhere to the normal distribution law.

The Sulak Vysokogornaya meteorological station is located at an elevation of 2923 m above sea level, 42°22’ N, 46°15’ E. The Akhty meteorological station is situated in the middle-mountain area of the Eastern Caucasus within the Republic of Dagestan, at 1016 m, 41°28’ N, 47°45’ E [*Bulygina et al.*, 2024]. An understanding of the magnitude of the annual average monthly precipitation totals in the mountainous zone of the Republic of Dagestan and their dynamics by decadal periods, which are also widely used in climate characterization, can be gained from Figure 2.

In the highland region of the Republic of Dagestan (RD), the years with the highest precipitation were revealed at the beginning of the study period. From 1961 to 1990, the average annual monthly sum was 99.4 mm/month (1192 mm/year).

In the mid-mountain zone of the Republic of Dagestan (Akhty meteorological station), the years with the highest precipitation occurred in 2001–2010, with an average annual of 36 mm/month (432 mm/year).

The minimum average annual precipitation was observed both at the beginning (31.48 mm/month) and at the end of the study period (31.43 mm/month), amounting to 378 mm/year. In the most recent decade, 2011–2020, the value of the average annual sums is the lowest.

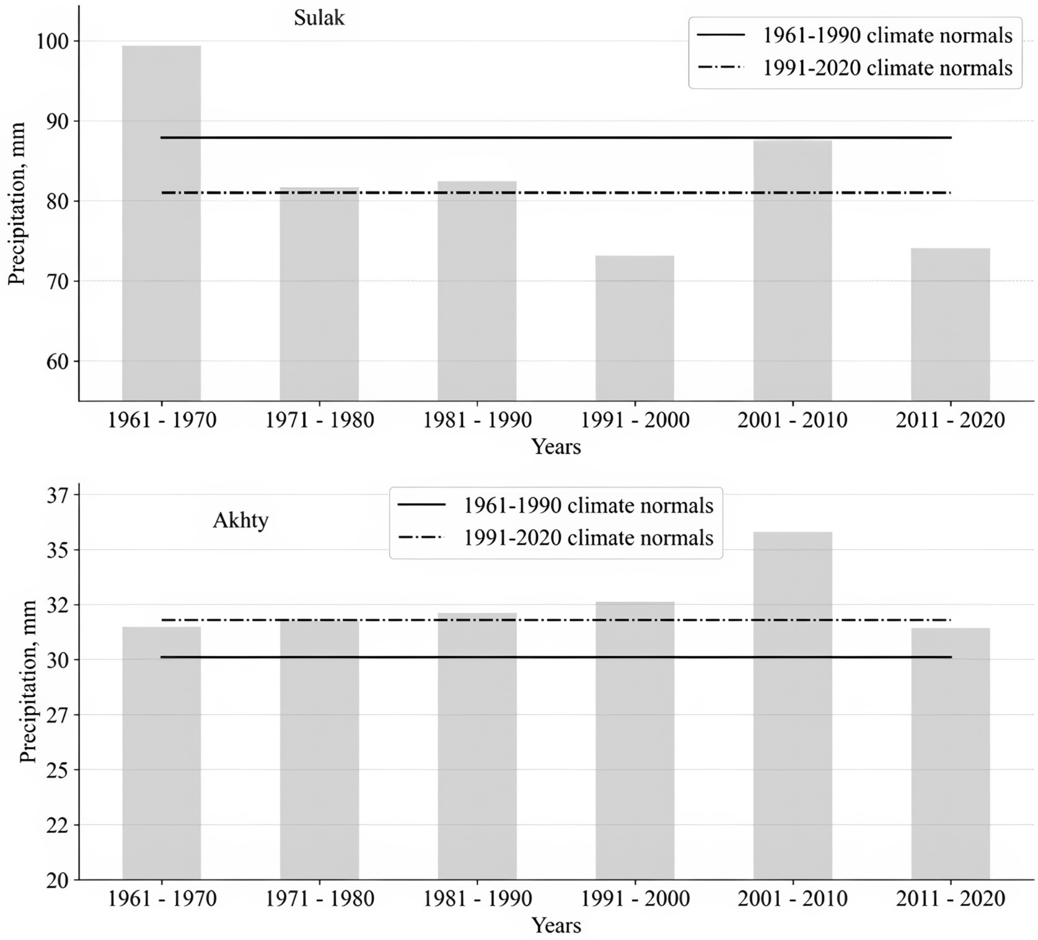

Figure 2. Dynamics of the average annual precipitation totals by decade for the Sulak Vysokogornaya (top) and Akhty (bottom) meteorological stations.

The results of calculations for statistically significant trends at a significance level of 0.1 for the period 1976–2023 are summarized in Figure 1.

In the high-mountain zone of the Eastern Caucasus (Sulak Vysokogornaya meteorological station), a trend of increasing precipitation in March has been detected, along with an increase in the number of days with precipitation exceeding 5 mm in March. There is also an increase in the number of days with precipitation exceeding 10–15 mm in July and an increase in the number of days with precipitation exceeding 20 mm in February.

The other identified statistically significant trends are negative. In spring, a decrease in precipitation was detected in April at an average rate of 10 mm per decade, which is associated with a decrease in the number of days with precipitation exceeding 1–5 mm.

In summer, a decrease in monthly precipitation totals in August occurs alongside a reduction in the number of days with precipitation exceeding 1–15 mm. In autumn, monthly totals in November are decreasing at an average rate of 16 mm per decade due to a decline in the number of days with precipitation exceeding 1–10 mm.

The Spearman's rank correlation coefficients for the identified trends can be interpreted as a trend stability/persistence measure, ranging from ±1 (indicating a perfectly stable/consistent process) to 0 (indicating a chaotic fluctuation of values). The trend stability measures of the detected trends rang from weak to moderate.

The results of calculations of statistically significant trends based on data from the Akhty meteorological station at a significance level of 0.1 for the period 1976–2023 are summarized in Figure 2.

Table 1. Statistically significant trends in climate characteristics of the precipitation regime, Sulak Vysokogornaya meteorological station, 1976–2023

Month/Season	I_{mean}	σ	Normal	$\tau_{Kendall}$	$p-$value	r_S	$p-$value	b_{Linear}	$p-$value
Monthly totals, mm									
March	73.11	35.65	True	0.25	0.0174	0.38	0.011	9.57	0.014
April	105.45	38.26	True	–0.18	0.0784	–0.27	0.08	9.57	0.014
August	101.59	58.66	False	–0.23	0.0238	–0.34	0.0227	–6.42	0.1404
November	46.4	34.8	True	–0.2	0.0482	–0.3	0.0417	–15.87	0.0133
Number of days with precipitation exceeding 1 mm									
April	12	4.2	False	–0.24	0.0255	–0.35	0.0175	–0.94	0.042
August	10.2	4.1	True	–0.21	0.0408	–0.33	0.0263	–1.06	0.0185
November	5.46	3.24	True	–0.2	0.0633	–0.29	0.0525	–0.61	0.0926
Number of days with precipitation exceeding 5 mm									
March	4.67	2.54	True	0.24	0.0227	0.38	0.0095	0.62	0.0269
April	6.28	2.64	True	–0.24	0.0267	–0.34	0.0218	–0.49	0.0929
August	5.61	2.76	True	–0.19	0.0692	–0.28	0.0566	–0.61	0.0447
Number of days with precipitation exceeding 10 mm									
March	2.2	1.68	True	0.25	0.0255	0.33	0.0263	0.44	0.0174
July	4.17	2.17	True	0.18	0.0913	0.25	0.0964	0.38	0.1154
August	3.37	1.98	True	–0.21	0.0565	–0.29	0.0518	–0.46	0.0358
November	1.5	1.47	True	–0.19	0.0923	–0.26	0.0834	–0.25	0.1241

Note: I_{mean} – mean monthly or seasonal precipitation total for the period of 1976–2023, mm; σ – standard deviation of the time series; $\tau_{Kendall}$ – Kendall's rank correlation coefficient; r_S – Spearman's rank correlation coefficient; b_{Linear} – slope estimate of the linear regression model, mm per decade; p-value – a measure of statistical significance for the Kendall's τ coefficient, Spearman's r coefficient, and the linear trend slope estimate b; Normal – logical flag for the distribution form of the series; equals True if the sample is normally distributed.

During the period under consideration (1976–2023), the positive trend in precipitation growth observed for 1961–2023 [*Korchagina*, 2024] remains intact. This trend is ensured by an increase in the number of days with precipitation exceeding 1 mm and 10 mm in March. In February, there has been an increase in the number of days with precipitation greater than 15 mm, while the change in the total monthly precipitation for February is statistically insignificant, indicating a redistribution of precipitation within the month in favor of days with more intense rainfall. Additionally, an increase in the average daily precipitation totals for both February and March has been observed.

In August, as in high-altitude areas, the monthly precipitation totals decrease at a rate of 4.4 mm per decade, but the degree of stability of the trend based on data from the Akhty meteorological station is lower.

A decrease in the number of days with precipitation has been observed in December (more than 1 mm) and in June (more than 10 mm).

3.2. Chechen Republic

The study was conducted using data from the Grozny meteorological station (256 m above sea level, 43°15’ N, 45°43’ E) and the Gudermes meteorological station (74 m above sea level, 43°21’ N, 46°7’ E) [*Bulygina et al.*, 2024]. The magnitude of the annual averaged monthly precipitation totals in the territory of the Chechen Republic (ChR) and their dynamics by decadal periods are presented in Figure 3. For the Grozny meteorological station, the climate norms for the periods 1961–1990 and 1991–2020 are identical.

The analysis of statistical characteristics of the time series of monthly precipitation totals, constructed using data from the Grozny meteorological station, shows that the

Table 2. Statistically significant trends in climatic characteristics of the precipitation regime, Akhty Meteorological Station, 1976–2023

Month/Season	I_{mean}	σ	Normal	τ_{Kendall}	$p-$value	r_S	$p-$value	b_{Linear}	$p-$value
Monthly totals, mm									
March	27.75	15.94	False	0.21	0.041	0.33	0.0308	3.34	0.0609
August	37.91	23.77	True	–0.17	0.1086	–0.24	0.1094	–4.4	0.0967
Number of days with precipitation exceeding 1 mm									
March	5.15	2.53	True	0.19	0.0723	0.27	0.0716	0.51	0.0703
December	2.83	1.84	True	–0.21	0.0497	–0.31	0.0368	–0.36	0.0801
Number of days with precipitation exceeding 5 mm									
August	2.24	1.59	True	–0.18	0.0995	–0.26	0.0864	–0.3	0.09
Number of days with precipitation exceeding 10 mm									
March	0.43	0.62	True	0.31	0.0097	0.4	0.0063	0.16	0.0155
June	1.76	1.32	False	–0.18	0.1095	–0.25	0.0886	–0.27	0.0653
August	1.17	1.04	True	–0.21	0.0603	–0.29	0.0504	–0.2	0.0874
Number of days with precipitation exceeding 15 mm									
February	0.09	0.28	False	0.21	0.0937	0.25	0.094	0.05	0.094
March	0.22	0.51	False	0.2	0.1059	0.25	0.0994	0.09	0.1199

highest percentage of outliers is found in December, amounting to 6.35%. For the Gudermes meteorological station, the highest percentage of outliers occurs in December and January, totaling 8.33%. All outliers are oriented towards an increase in humidity.

The results of the calculations of statistically significant trends in the series of monthly and seasonal totals based on data from the Grozny and Gudermes meteorological stations are presented in Figure 3.

Table 3. Statistically significant trends in average monthly and average seasonal precipitation (mm), meteorological stations of the Chechen Republic, 1976–2023

Month/Season	I_{mean}	σ	Normal	τ_{Kendall}	$p-$value	r_S	$p-$value	b_{Linear}	$p-$value
Grozny meteostation									
March	29.13	15.40	True	0.37	0.0007	0.52	0.0007	5.49	0.0003
April	37.51	23.39	True	0.22	0.0426	0.35	0.0278	3.84	0.1184
May	63.13	32.45	False	0.26	0.0153	0.39	0.0123	6.83	0.0427
September	38.80	35.38	False	0.22	0.0503	0.30	0.0577	6.79	0.0664
Spring	43.41	16.85	True	0.36	0.0010	0.50	0.0010	5.40	0.0013
Autumn	38.06	18.35	False	0.29	0.0076	0.45	0.0038	4.53	0.0166
Winter	26.37	8.93	True	0.23	0.0409	0.31	0.0535	1.93	0.0373
Year	42.10	9.44	True	0.29	0.0100	0.46	0.0035	3.06	0.0011
Gudermes meteostation									
August	4.44	2.89	False	–0.16	0.1227	–0.25	0.0823	–0.57	0.0570

As in the mountain zone of the Eastern Caucasus, a steady increase in precipitation characteristics has been observed in the Chechen Republic during March. This includes an increase in monthly totals at a rate of 5.5 mm per decade and an increase in the number of days with precipitation exceeding 1–10 mm at a rate of 0.5–1 days per decade.

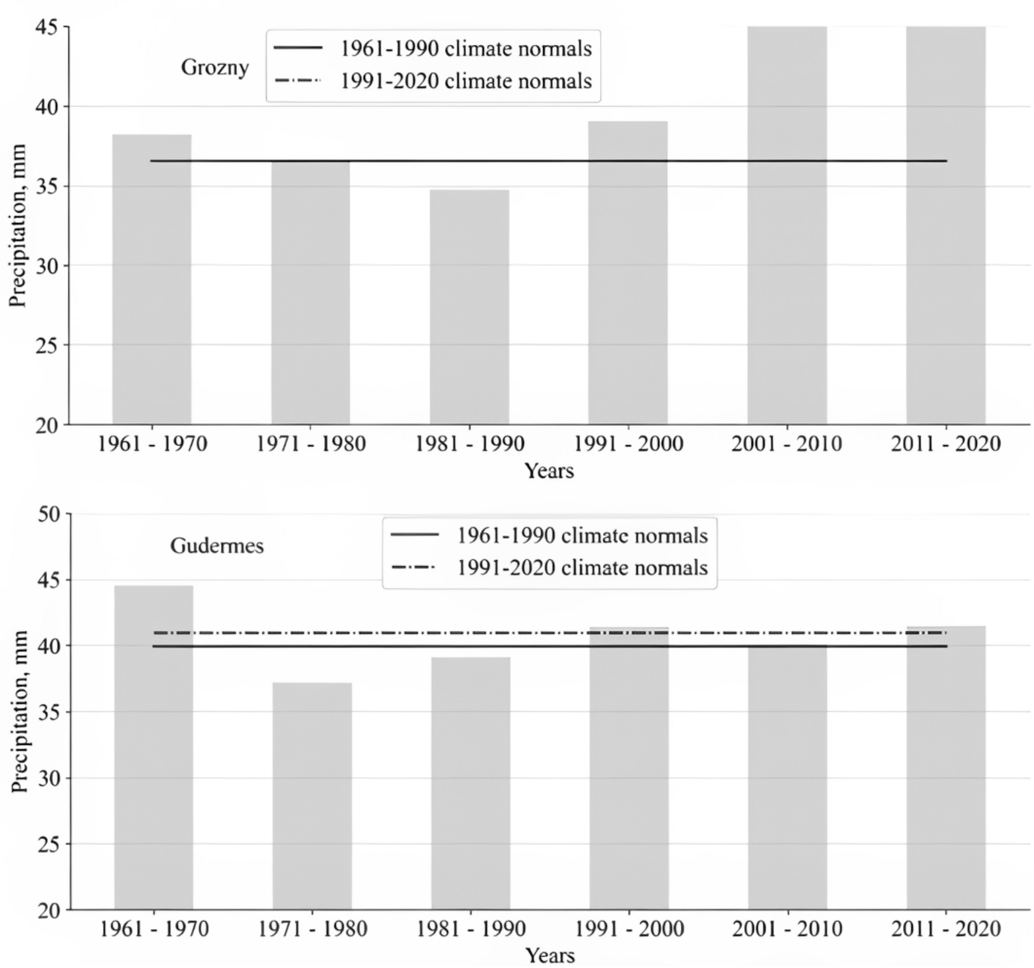

Figure 3. Dynamics of the annual average monthly precipitation totals over ten-year periods, Grozny meteorological station (top) and Gudermes meteorological station (bottom).

However, unlike in the Republic of Dagestan, an increase in precipitation totals has been noted in April at a rate of 4 mm per decade and in May at a rate of 7 mm per decade. The trend assessment for May is unreliable due to the deviation of the series from a normal distribution; therefore, we turn our attention to the trend persistence measure, expressed by Spearman's rank correlation coefficient (r_S). Its value falls into the moderate qualitative category and is 0.39.

The increase in April totals is accompanied by a growth in the number of days with precipitation exceeding 1–15 mm.

An increase in average monthly totals was also detected in September (r_S = 0.3, $\tau_{Kendall}$ = 0.22). This is accompanied by an increase in the number of days with precipitation exceeding 1–20 mm.

Unlike in the highland region, positive trends in average seasonal precipitation totals are evident here for all seasons and for the whole year, with the exception of summer.

Among local features, an increase in the number of days with precipitation over 1 mm in December and over 10mm in October has been revealed.

3.3. Dangerous natural processes of hydrometeorological nature

Based on data for dangerous and adverse hydrometeorological events, which have caused material and social damage in Russia, provided by the VNIIGMI MCD – World Data Center [*Shamin et al.*, 2019], samples of phenomena occurring in the Republic of Dagestan and the Chechen Republic have been formed. For the selected data, the number of different phenomena related to atmospheric precipitation (snow, hail, downpours, rain, mixed precipitation) has been calculated. The results of the calculation of the annual course of adverse hydrometeorological events, recorded in the territory of RD (top) and ChR (bottom), from 1991 to 2023, are shown in Figure 4.

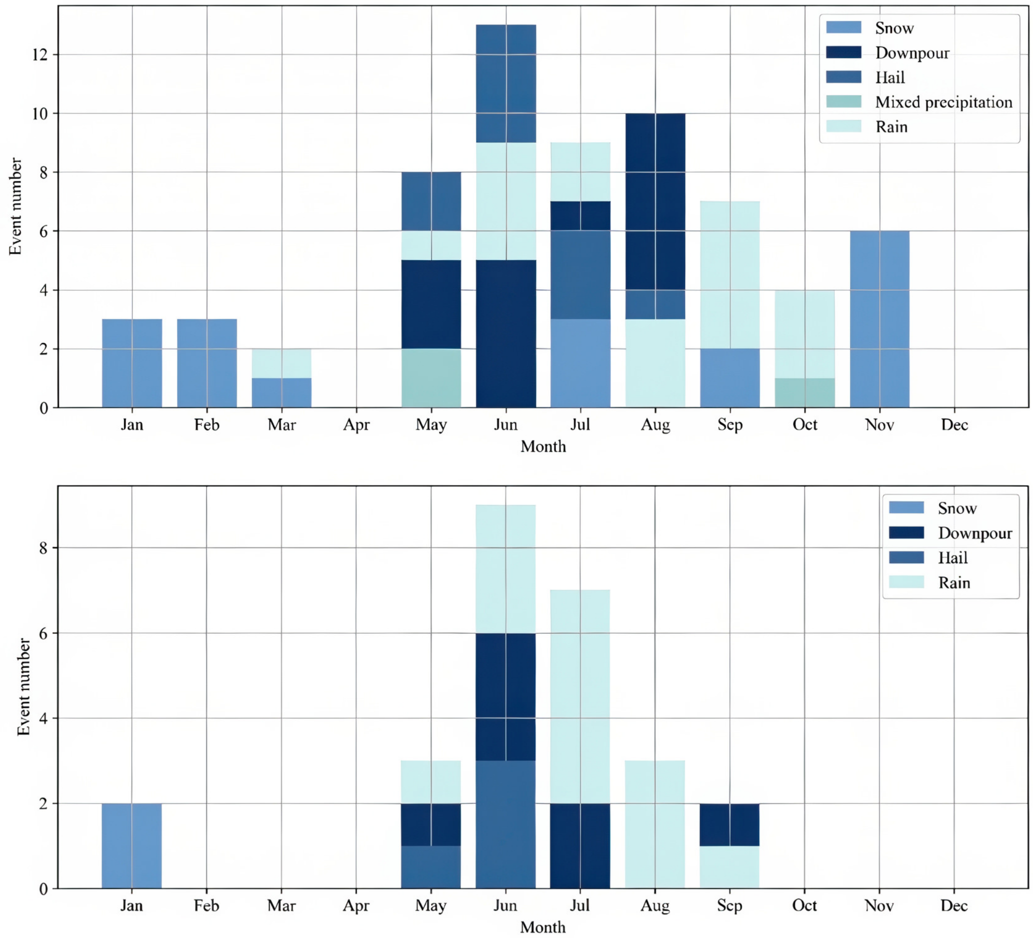

Figure 4. Annual distribution of the number of dangerous hydrometeorological events in the Republic of Dagestan (top) and the Chechen Republic (bottom) for the period 1991–2023.

In the Republic of Dagestan, the maximum number of adverse events was recorded in June and is related to hailstorms. The safest months in the region, from this perspective, are April and December. Adverse events associated with rain have a primary peak in June-July and a secondary peak in September, which corresponds to the annual precipitation pattern in the low-mountain zone.

As shown in the calculations, in the Chechen Republic, the maximum number of hydrometeorological disasters that caused damage between 1991 and 2023 also occurred in June, as in RD. The period of dangerous rains and downpours lasts from May to September, which nearly coincides with the flood and mudflow hazard season in the republic.

4. Conclusion

The study of changes in the precipitation regime in the high-mountain zone of the Republic of Dagestan (RD) from 1976 to 2023 revealed no statistically significant changes in the series of average seasonal precipitation totals. A moderately stable increase in the monthly totals and the number of days with heavy precipitation in March was observed. In the high-mountain zone, a weakly stable increase in the number of days with precipitation exceeding 15 mm was found in July and February.

In the mid-mountain part of the RD territory, a decrease in various precipitation regime characteristics was observed in August, and in the high-mountain zone, this trend extended to April and November.

In the Chechen Republic (ChR), the overwhelming number of detected trends were positive. Moderately stable trends in average seasonal precipitation totals were observed for all seasons and the entire year, except for summer.

The general regional trends in the precipitation regime changes in the Eastern Caucasus republics can be attributed to an increase in various precipitation regime characteristics in March and a decrease in August.

A comparison of the identified trends with the annual distribution of dangerous hydrometeorological events suggests that in the mountain part of the region, the trend toward a decrease in precipitation regime characteristics during the high flood and mudflow danger season will persist. At the same time, in the high-mountain zone, there may be an increase in the rainfall component contributing to the formation of dangerous hydrological events in July, which is one of the most hazardous months, associated with a weakly stable increase in the number of days with heavy precipitation.

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