A STUDY OF CHANGES IN THE PRECIPITATION REGIME IN THE REGION OF LONG-TERM HAIL SUPPRESSION ACTIVITIES IN THE CENTRAL REGION OF THE REPUBLIC OF MOLDOVA

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Abstract

The paper presents the results of a comparative analysis of the statistical characteristics of summer precipitation totals for the period of 50–60 years of their observations on hail-protected and adjacent territories. It is shown that, against the background of the general tendency of decrease in the amount of summer precipitation, an increase in the totals in a range of 4–9% is recorded at weather stations located in the center of the protected territory compared with the amount recorded at the weather station outside the hail-protected territory.

Results of theoretical and experimental studies show the possibility of changing the summer precipitation totals by active impacts (AIs) on hail processes both on protected (PTs) and adjacent territories (ATs) [1, 2]. A decrease in the amount of precipitation under the action of AIs on PTs is attributed to a reduction in the duration and intensity of their fallout from reagent-seeded convective cells owing to the premature destruction of the cells. On the territory leeward to the PTs, the amount of precipitation can increase up to 15% of the seasonal norm. In some experiments, a long-term aftereffect of cloud seeding (increase in precipitation) after AI seasons with the use of silver iodide reagents was recorded on the ATs [4]. On the basis of experimental data, it can be assumed that some elements of the cloud seeding aftereffect can lead to a change in the precipitation regime on PTs directly during the periods of hail-suppression activities [6]. It was found that a significant role in this effect is played by changes in the climatic factors in the region [5].

Taking into account the urgency of the problem, in the 1980s, special experiments were conducted on the PTs in Moldova; they showed that the effect of decrease in the amount of precipitation takes place owing to the suppression of "intense showers" by AIs. This decrease is partially compensated by an increase in the amount of "moderate and significant" rainfalls with a total balance for the season of minus 4% [3]. This value is an expectation-driven index.
In this aspect, of undoubted scientific and practical interest are estimates of the actual change in the precipitation regime in regions of long-term and systematic activities on AIs. This region is the Republic of Moldova, where hail-suppression activities based on the rocket technology have been carried out since 1964.

In this paper, estimates of changes in the precipitation regime in the central part of Moldova are presented on the basis of the historical data of the precipitation network of the Hydrometeo Service of the Republic of Moldova. The research results are based on the statistical processing of summer precipitation totals (May–August) by means of MS Excel at the following weather stations (WSs):

(1) WS Cornesti; years of observation 1946–2014. It is located in the center of the region of hail-suppression activities in the Republic of Moldova from the very beginning of their onset (1964).
(2) WS Ungheni; years of observation 1954–2014. It is located 23 km to the west of WS Cornesti directly near the region of AIs (control territory (CT)).
(3) WS Falesti; years of observation 1958–2014. It was in the PT in 1978–1999 and 2007–2014.
(4) WS Orhei; years of observation 1949–2014 (CT). It is located 62 km to the east of Cornesti directly outside the region of AIs. Relative to Cornesti, this is the direction of the main motions of reagent-seeded hail-hazardous clouds on the PT.
The authors understand the complexity of solving the problem owing to the low density of the analyzed precipitation network with respect to the characteristics of the spatiotemporal variability of precipitation from convective clouds.

1. Brief Information on Hail-Suppression Activities in the Republic of Moldova in 2014

- Beginning of hail-suppression activities dates back to 1964 with the center in the village of Cornesti.
- In the period of 1964–1982, PbI_2-based formulations were used as a reagent for cloud seeding; since 1983, AgI-based formulations have been used everywhere.
- Most probably, AIs, regardless of the motion of reagent-seeded clouds, will affect the precipitation regime recorded at WS Cornesti because the predominant intrusion of hail processes into the territory of the Republic of Moldova has a western component.
- In the season of 2000, no hail-suppression activities were carried out in the Republic of Moldova. In 2001, they resumed in July.

2. Time Variation in Summer Precipitation Totals: Coefficients α are a Trend from Regression Equations

Changes in the precipitation regime were estimated using arrays of data on totals recorded at WSs located in the different regions of the central part of Moldova for the years indicated above. This approach is a widespread and important form of studying the meteorological phenomena; it gives an idea of the change in their qualitative and quantitative characteristics over time.

Figure 1 and Tables 1–3 show the results of analysis of summer precipitation for WSs Cornesti, Ungheni, and Orhei for the entire period of observations.

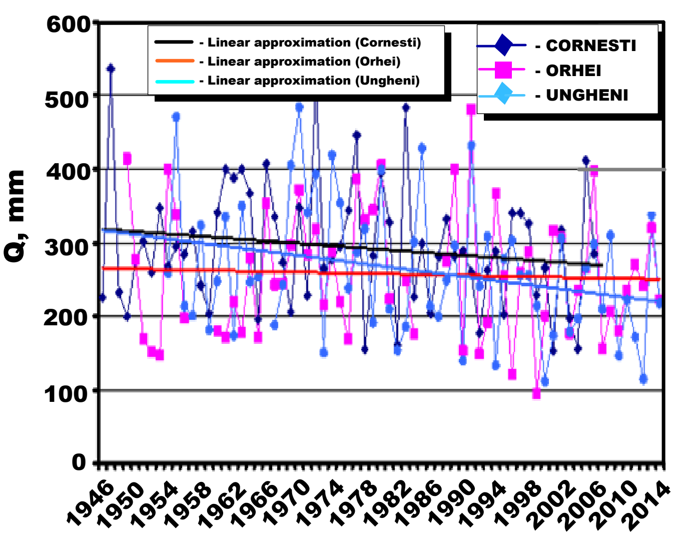

Fig. 1. Summer precipitation totals of and their trends (linear) for WSs Cornesti, Ungheni, and Orhei for the entire period of observations.

Table 1. Values of coefficients α (mm/season) of regression equations for summer precipitation totals at the WSs in different measurement periods

WS	α (mm/season)		
	Over the entire period of observations of precipitation	Over the entire period of AIs (1964–2014)	Over the AI period of 1983–2014
Falesti	0.2758	- 0.0388	- 0.7078
Ungheni	- 1.4238	- 2.082	- 2.0235
Orhei	- 0.2205	- 0.2445	- 0.4785
Cornesti	- 0.5646	-1.3623	- 1.9183

Table 2. Relationship between the amount of precipitation at WS Cornesti and the data of other WSs in different observation periods

WS	Regression equations before AIs and in the period of AIs	R^2 before AIs and in the period of AIs
Cornesti–Falesti	y = 0.8699x – 0.1916 y = 0.6582 + 90.165	0.4527 0.4745
Cornesti–Ungeni	y = 0.8009x + 77.572 y = 0.7858x + 90.979	0.6307 0.6848
Cornesti–Orhei	y = 0.3124x + 200.39 y = 0.49x + 167.2	0.0846 0.2323

R^2 is the square of the mixed correlation; it is a number of 0 to 1, which represents the proximity of the trend line values to the actual data. The trend line most realistically represents the facts if R^2 is close to unity.

Table 3. Statistical characteristics of summer precipitation totals for periods of their measurements

Statistical characteristics	WS			
	Falesti	Ungeni	Orhei	Cornesti
Measurement period, years	1958–2014	1954–2014	1949–2014	1946–2014
Q_{av}, mm	273	260	247	294
Q_{max}, mm	491	484	484	536
Q_{min}, mm	107	109	95	95
σ, mm	84.5	91.5	84.8	96.6
Coefficient of variation (v)	0.31 *(homogeneous series)*	0.35 *(inhomogeneous series)*	0.34 *(inhomogeneous series)*	0.33 *(homogeneous series)*

Analysis of the time variation in the summer precipitation totals and coefficient α showed the following:

- In the studied WSs, regardless of their location relative to the region of hail-suppression activities, except for WS Falesti, there has been a steady tendency to decrease in the summer precipitation totals over the 60-year period. The largest of them — $\alpha = -1.42$ mm/season—was recorded at WS Ungheni, the smallest — $\alpha = -0.22$ mm/season—at WS Orhei.
- In the series of precipitation totals, a large temporal variation is recorded: up to 2.0–2.5 times in the cycle of two to four years; it complicates the identification of the effect of AIs on their change.
- In the period of AIs (1964–2014), at all the WSs, trends $\alpha < 0$. The greatest trend — $\alpha = -1.36$— was recorded at WS Cornesti. For the period of 1983–2014 (use of AgI in AIs) for WS Cornesti, $\alpha = -1.91$; that is, an increase in the trend of decrease in the summer precipitation totals is recorded, while at WS Ungheni (CT) the trend value hardly changed at all.
- During the period of 1983–1984 (period of use of a reagent based on AgI), the trend to decrease in the amount of precipitation increased according to the data of WS Orhei.
- Based on the data presented in the section, including statistical characteristics, it is impossible to make unambiguous conclusions about any effect of AIs on changes in summer precipitation totals recorded at WSs located in the region of hail-suppression activities.

3. Results of Analysis of Autocorrelation Functions of the Series of Summer Precipitation Totals

Studies of the relationship between summer precipitation totals revealed elements of quasi-periodicity in their time variation. The presence of these structures is confirmed by analysis of second-order autocorrelation functions, which are the basic tool for analyzing time series (Figs. 2, 3). (*Autocorrelation is a statistical relationship between random variables from one series taken with a shift, for example, over time*).

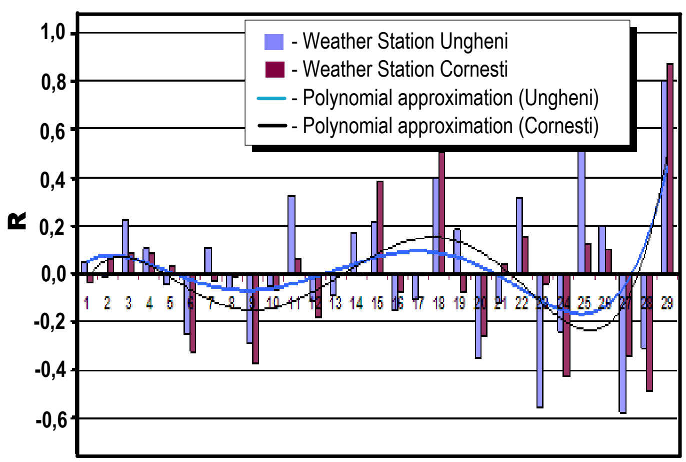

Fig. 2. Second-order autocorrelation functions of the time series of summer precipitation totals for WSs Cornesti and Ungeni.

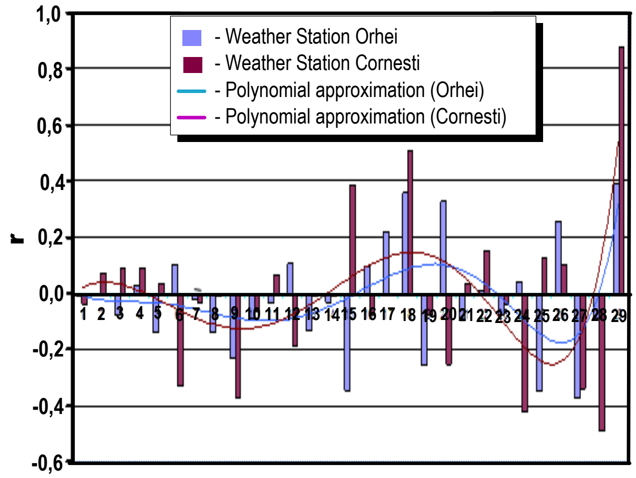

Fig. 3. Second-order autocorrelation functions of the time series of summer precipitation totals for WSs Cornesti and Orhei.

The above figures suggest the following:

- Historically, the change in summer precipitation totals has a pronounced quasi-periodic nature with a period of about 30 years. Their greatest synchronization is found in the transfer of air masses Ungheni–Cornesti–Orhei.
- The uniformity of the structures of autocorrelation functions for different WSs can indicate a unified natural mechanism of their formation in the studied territory.

4. Verification of the Hypothesis about the Possible Effect of AIs on Summer Precipitation Totals for WSs Located on the PTs: Double Ratios

For a statistical verification of the hypothesis of a possible change in the amount of summer precipitation in the region of AIs on hail processes, estimates of series of precipitation totals recorded at the studied WSs were made using the **t**-test (Student's criterion) and the **F**-criterion (Fisher criterion). Hypotheses about changes in the statistical characteristics of precipitation series during the period of hail-suppression activities can be adopted in the presence of these changes with a probability of $P \geq 95\%$ (level of statistical significance of 0.05).

To estimate quantitative changes in precipitation totals over the period of hail-suppression activities at WSs located on the PTs in comparison with changes recorded at WSs located in ATs, the so-called double ratio method was used (formula 1); it is commonly used in similar studies [4]:

$$\left(\frac{\overline{Q}_{\text{ÇÒ}}}{\overline{Q}_{\text{ÊÒ}}}\right)_{\text{ÀÂ}} \Bigg/ \left(\frac{\overline{Q}_{\text{ÇÒ}}}{\overline{Q}_{\text{ÊÒ}}}\right)_{\text{äîÀÂ}} \qquad (1)$$

Table 4. Estimates of changes in the amount of precipitation by the t-test (for independent samples, comparison of samples before AIs with the period of AIs)

WS	**Sample length (number of years)**	**Calculated t-test value**	**Tabulated t-test value for P = 95%**	**Implementation of hypothesis H_0 (no changes)**
Falesti	**20/37**	**0.688**	**1.959**	**H_0 is accepted**
Ungheni	**14/47**	**0.623**	**1.959**	**H_0 is accepted**
Orhei	**47/19**	**0.154**	**1.959**	**H_0 is accepted**
Cornesti	**22/47**	**0.979**	**1.959**	**H_0 is accepted**

For P = 95%, t values calculated from the actual data are lower than the tabulated t values for all the WSs. This means that, for the compared periods, this test has not revealed any significant changes in the series of summer precipitation totals.

Table 5. F-criterion values and significance levels in estimating the effect of AIs (comparison of samples before AIs with the period of AIs)

WS	Beginning of precipitation measurements	F-criterion		
		calculated F value	F_α (tabulated)	
			P = 95%	P = 50%
Falesti	1958	1.046	1.84	0.98
Ungheni	1954	1.173	2.64	1.05
Orhei	1949	1.324	1.88	0.97
Cornesti	1946	2.105	1.84	0.97

The F value calculated for P = 95% is higher than the tabulated value only for WS Cornesti; this fact indicates statistically significant changes in the series of precipitation amounts for this WS in comparing the data before and during the hail-suppression activities.

The calculations revealed the following:

- In the series of precipitation amounts for all the WSs, no statistically significant changes determined by the t-test were revealed (for independent samples, comparison of the samples before AIs with the AI period).
- Analysis of the series of precipitation totals for WSs using the F-criterion (comparison of sample variances before AIs with the AI period) showed that the null hypothesis with a probability of more than 95% can be rejected only for WS Cornesti; that is, statistically significant changes were revealed.
- The presence of an "additional" source that affects the formation of the spectrum of precipitation totals at WS Cornesti during the hail-suppression activities is indirectly confirmed by the specific features of the probability of distribution of these totals at WS

Ungheni: the presence of a second mode in the region of large precipitation totals for WS Cornesti.

- Comparative analysis of summer precipitation totals at WSs Cornesti and Falesti (PTs) with the data of WSs located outside the PTs using the "double ratio" method showed that the gain in precipitation recorded at WSs Cornesti and Falesti relative to WS Ungheni is 4.6% and 9.0%, respectively; in comparison with WS Orhei (territory leeward to the PT), minus 6.3% and minus 4.0%

5. Conclusions

Comparative analysis of statistical data on precipitation in summer periods at WSs located on PTs and ATs (CTs) has shown the following:

1. At all the WSs, regardless of their location relative to the region of hail-suppression activities, except for WS Falesti, over the 60-year period, there has been a steady trend of decrease in the summer precipitation totals.
2. Historically, the change in the summer precipitation totals has a pronounced quasi-periodic pattern with a period of about 30 years.
3. During the period of activities on AIs at WSs located on the PTs, an increase in the negative values of trends in summer precipitation totals was observed, especially in 1983–2014, i.e., in the period of use of silver iodide. In the CTs, the changes in the trend values in this period are insignificant.
4. A high correlation between the summer precipitation totals recorded at WSs located on the PTs with the data of WS Ungheni (territory windward to the PT), regardless of the period of precipitation measurement, has been revealed. This fact can indicate the priority of unified natural sources (mechanisms) of their formation.
5. The values of trends in precipitation totals (mm/season) for the period of 1964–2014 are as follows: for WS Ungheni, minus 2.08; Orhei, minus 0.24; Falesti, minus 0.03; and Cornesti, minus 1.36.
6. Differences in the trends of summer precipitation totals at WSs located on the PT and CT before the beginning of hail-suppression activities and during the period of activities were evident as an increase in the summer precipitation totals for the period of AIs at WSs Cornesti and Falesti relative to WS Ungheni by 4.6% and 9.0%, respectively; in comparison with WS Orhei, minus 6.3% and minus 4.0%, respectively.
7. Statistical verification of the hypothesis of changes in the characteristics of summer precipitation totals at WS Cornesti (PT) by the Fisher's criterion has confirmed this assumption at the level of statistical significance of 0.05 (95%). For other WSs, this hypothesis has been found to be inapplicable.

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