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Spatiotemporal distribution of heavy and extreme snowfalls in the Transcarpathian region

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Abstract— This paper presents a spatiotemporal analysis of the dynamics of heavy and extreme snowfalls in the Transcarpathian region during 1990-2019. Data on snowfalls are obtained from the observation points of the state hydrometeorological network of the Transcarpathian Regional Center of Hydrometeorology. Also there are data included from the Pozhezhevska snow avalanche station (Ivano-Frankivsk region) as a representative observation point for the highland zone of the eastern part of the Transcarpathian region. The analysis took into account the date of snowfall, the amount of precipitation that fell during the snowfall,l and its duration. The recurrence of different indicators of snowfall distribution was calculated for each observation point separately for the specified thirty-year period. Some results were mapped by the isolines using kriging interpolation. Spatio-temporal heterogeneities and regularities in the distribution of heavy and extreme snowfalls have been revealed.
Key-words: heavy snowfall, extreme snowfall, Transcarpathian region, recurrence, trend, distribution, kriging interpolation

1. Introduction

Precipitation is one of the main indicators of climate. In most cases, rainfall is uneven, especially over mountainous areas (*Barry,* 1984). Natural meteorological phenomena associated with precipitation are characterized by significant variability and discreteness in space and time, which complicates their study (*Babychenko,* 1991; *Lipinskyi et al.,* 2006; *Lohvynov et al.,* 1972,1973; *Sakaly,* 1985).

The distribution of precipitation can be extremely uneven both during the year and during one season. This also applies to heavy and extreme snowfalls, of which there may be several cases in one year and dozens in another. At the same time, their intensity, duration, and area of precipitation vary greatly, which complicates weather forecasting and leads to disruptions of various sectors of the national economy and infrastructure (*Acar* and *Gönençgil,* 2019; *Lukić et al.,* 2018; *Balabukh,* 2013; *Osadchyy* and *Babychenko,* 2012). All over the world and in Ukraine in particular, the frequency of extreme weather events is increasing, among which heavy and extreme precipitation takes the first place (*Balabukh,* 2008; *Lohvynov et al.,* 1972; *Osadchyy* and *Babychenko,* 2012; *Pachaury* and *Mayer,* 2014). That is why scientists raise the issue of long-term dynamics of precipitation, especially in conditions of climate change and increasing frequency of weather anomalies. The policy of governments on climate change has been ratified by many documents at national and international levels (*Tykhomyrova,* 2018).

Insufficient attention has always been paid to the study of heavy and extreme snowfalls, especially in the Ukrainian Carpathians. The main interest of scientists was limited to heavy and extreme rains, heavy and extreme prolonged rains, as well as heavy and extraordinary showers (*Balabukh,* 2008; *Voloshyna* and *Knysh,* 2010; *Pyasetska,* 2001; *Lukić et al.,* 2018). The risks and dangers of heavy and extreme snowfalls are significantly underestimated. First of all, such snowfalls are the causes of avalanches and traffic jams. During intensive falling sleet, it often sticks to various surrounding objects, breaking tree branches, breaking power and communication wires, disrupting constructions and utilities. Late snowfalls make it impossible to carry out spring agricultural work *(Lipinskyy et al.,* 2006; *Lohvynov et al.,* 1973; *Sakaly,* 1985).

The purpose of this work was to analyze the long-term changes in the number, intensity and spatial distribution of heavy and extreme snowfalls in the Transcarpathian region.

2. Materials and methods

2.1. Research area

The Transcarpathian region is located in the extreme west of Ukraine. It borders on Lviv and Ivano-Frankivsk regions, as well as four European Union countries: Poland, Slovakia, Hungary, and Romania. The area of the region is 12.8 thousand km^2 (2.1% of the territory of Ukraine). Thus, the Transcarpathian region is located in Central Europe, which has important cross-border significance (*Rishko,* 2017).

The Transcarpathian region is a unique ecological system of western Ukraine with a variety of relief and climatic conditions due to the vertical clarity and diversity of landscapes. Its territory is protected from the north and east by the Ukrainian Carpathians, from the northwest by the Tatra Mountains, from the south by the western Romanian mountains and the Maramureş massif *(Rishko,* 2017; *Sakaly,* 1985; *Lohvynov et al.,* 1973).

About two thirds of the territory of Transcarpathia is occupied by mountains with the highest peak of Ukraine (Hoverla, 2061 meters above sea level). The region is located on the southwestern slopes of the Ukrainian Carpathians (Eastern Carpathians) and on the adjacent Transcarpathian lowlands, which are part of the Middle Danube lowlands (*Herenchuk,* 1981).

The climate of Transcarpathia is temperate-continental with sufficient and excessive humidity, unstable spring, not very hot summer, warm autumn, and mild winter. The average annual wind speed in different places is 1.2–2.4 m/s. The maximum speed, registered in the area of the cities of Khust and Mizhhirya and in the mountain meadows, reaches about 40 m/s. In January, the average monthly long-term temperature is -7.8 °C in the mountains, while in the lowlands (Uzhhorod) it is only -3.1 °C, and in summer it is 11–14 °C in the highlands and 20–21 °C in the lowlands. The amount of precipitation changes depending on the height of the territory. The average annual rainfall is 600–800 mm in the lowlands, and 1000–1500 mm in the mountains (in a year of high water content it is up to 2500 mm) *(Babychenko* and *Dyachuk,* 2003; *Sakaly,* 1985).

Fig. 1 shows a map of the research area with the geographical location of the observation points of the Ukrainian Hydrometeorological Center, from which data were collected on heavy and extreme snowfall for this work.

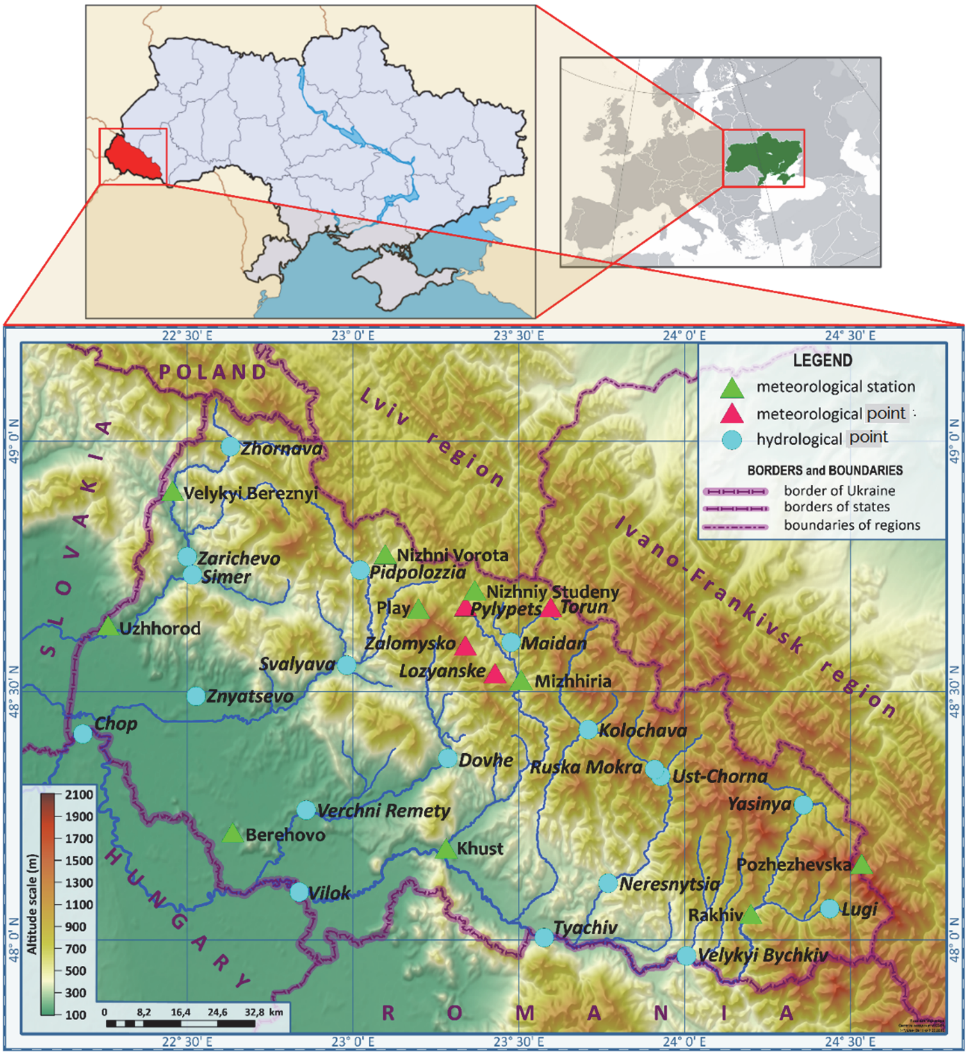

Fig. 1. Geographical location of hydrometeorological observation point involved in the research.

2.2. Data and methods

We used data only from those points that conducted continuous meteorological observations of precipitation during 1990–2019 to ensure temporal representativeness. In total, data from 10 meteorological stations, 4 meteorological points and 19 hydrological observation points are included in the work (*Table 1*).

According to the methodological guidelines of the Central Geophysical Observatory named after Borys Sreznevskyi (CGO) and the Ukrainian Hydrometeorological Center (UkrHMC) a clear criteria is defined for heavy and extreme snowfall (*Table 2*) (*Humonenko et al.,* 2019).

Table 1. Lists of points of hydrometeorological observations

Name	Latitude (north)	Longitude (east)	Altitude (m)
1. MS Berehovo	48°13′02′′	22°38′12′′	112
2. MS Uzhhorod	48°37′58′′	22°15′39′′	115
3. MS Khust	48°11′07′′	23°16′49′′	166
4. MS Velykyi Bereznyi	48°54′05′′	22°27′19′′	209
5. MS Rachiv	48°03′08′′	24°12′00′′	438
6. MS Mizhhiria	48°31′26′′	23°30′23′′	456
7. MS Nizhni Vorota	48°46′30′′	23°05′49′′	500
8. MS Nizhniy Studeny	48°42′10′′	23°22′01′′	615
9. MS Play	48°39′59′′	23°11′49′′	1330
10. MS Pozhezhevska	48°09′14′′	24°32′03′′	1439
11. MP Zalomysko	48°37′01′′	23°20′10′′	785
12. MP Lozyanske	48°32′49′′	23°25′34′′	572
13. MP Pylypets	48°39′45′′	23°19′20′′	618
14. MP Torun	48°40′23′′	23°35′07′′	827
15. GP Velykyi Bychkiv	47°58′03′′	24°00′22′′	295
16. GP Verchni Remety	48°15′44′′	22°51′30′′	118
17. GP Vilok	48°05′47′′	22°50′13′′	114
18. GP Dovhe	48°22′00′′	23°17′08′′	172
19. GP Zhornava	48°59′22′′	22°37′45′′	334
20. GP Zarichevo	48°46′13′′	22°29′57′′	154
21. GP Znyatsevo	48°29′28′′	22°31′03′′	108
22. GP Kolochava	48°25′26′′	23°42′34′′	567
23. GP Lugi	48°03′47′′	24°26′15′′	632
24. GP Maidan	48°36′50′′	23°27′50′′	503
25. GP Neresnytsia	48°06′51′′	23°46′09′′	299
26. GP Pidpolozzia	48°44′35′′	23°01′15′′	362
27. GP Ruska Mokra	48°20′39′′	23°54′33′′	563
28. GP Svalyava	48°33′11′′	22°58′49′′	193
29. GP Simer	48°44′03′′	22°30′53′′	152
30. GP Tyachiv	48°00′17′′	23°34′33′′	211
31. GP Ust-Chorna	48°19′49′′	23°55′39′′	529
32. GP Chop	48°24′56′′	22°11′04′′	101
33. GP Yasinya	48°16′21′′	24°21′31′′	650

Note: MS – meteorological station, MP – meteorological point, GP – hydrological point

Natural meteorological phenomena of the II level of danger (NMP II) are natural phenomena that in terms of quantitative indicators, duration, and territory of threat, pose a threat to the population and disrupt the functioning of the economic complex of the country (*Humonenko et al.,* 2019).

Natural meteorological phenomena of the III level of danger (NMP III) are natural phenomena that, according to quantitative indicators, duration, and area of distribution, pose a threat to human life in large areas, lead to large-scale damage to the country's economic complex (*Humonenko et al.,* 2019).

Only those cases of snowfalls were taken into account, which in quantitative and temporal characteristics reached the corresponding values specified in *Table 2.*

Table 2. Criteria for heavy and extreme snowfalls approved by CGO and UkrHMC from January 1, 2019

Phenomenon	**Criterion of the natural phenomenon of the II level of danger (NMP)**		**Phenomenon**	**Criterion of the natural phenomenon of the III level of danger (NMP)**	
	quantitative indicator	**duration**		**quantitative indicator**	**duration**
heavy snowfall	20-29 mm	≤12 hours	extreme snowfall	≥30 mm	≤12 hours

Data on heavy and extreme snowfalls were obtained by sampling from various sources of information, thus multiple verifications were performed. The basis of the database was the monthly «Tables of meteorological and agrometeorological observations», which are compiled by all meteorological stations. For meteorological and hydrological points, the information was obtained from the monthly «Tables of meteorological observations», and if they were not available, then from the «Books for recording hydrological observations». The information was also supplemented from the annual «Weather review and natural hydrometeorological phenomena on the territory of Ukraine», from the database METEOBASE developed by UkrHMC, and from «Reports on natural hydrometeorological phenomena» obtained directly from meteorological stations. The single program of meteorological observations of precipitation at stations and observation points made it possible to unify and combine data for research.

Statistical data processing, reliability assessment of the used series of observations, and accuracy testing of the obtained quantity were performed using the methods of mathematical statistics *(Battalov,* 1968; *Dubrovskaya* and *Knyazev,* 2011; *Kobysheva* and *Narovlyanskyy,* 1978; *Shkolnyy et al.,* 1999).

The calculation of arithmetic mean (perennial) values ($\overline{x}$) was performed by the formula:

$$\overline{x} = \frac{\sum x_i}{n}, \tag{1}$$

where x_i are the individual values of the researched feature, n is the the number of years, cases or observations.

To characterize the variability of heavy and extreme snowfalls, the standard deviations of individual values (σ) from the long-term average, as well as the coefficients of variability (variation) (C_v) were calculated by the formulas:

$$\sigma = \sqrt{\frac{\sum(x_i - \overline{x})^2}{n}}, \tag{2}$$

$$C_v = \frac{\sigma}{\overline{x}}. \tag{3}$$

All mathematical calculations of indicators were performed in Microsoft Excel 2016.

Mapping of data on heavy and extreme snowfalls was carried out using the software package for cartographic modeling Surfer 15, and the isoline method was used. Interpolation was performed by the kriging method, as the one that most accurately uses statistical parameters to find the optimal estimate in terms of minimum mean deviation when constructing surfaces, cubes, and maps (*Abdullin* and *Shikhov,* 2017; *Katsalova* and *Shpyh,* 2013; *Mkrtchyan* and *Schuber,* 2013). All cartographic materials are created in an equilateral cylindrical projection of the Mercator using a three-dimensional coordinate system WGS-84.

3. Results

During 1990–2019, 453 isolated cases of heavy and 125 cases of extreme snowfall were recorded in the research area. The long-term distribution of the number of heavy and extreme snowfalls is shown in *Fig. 2.*

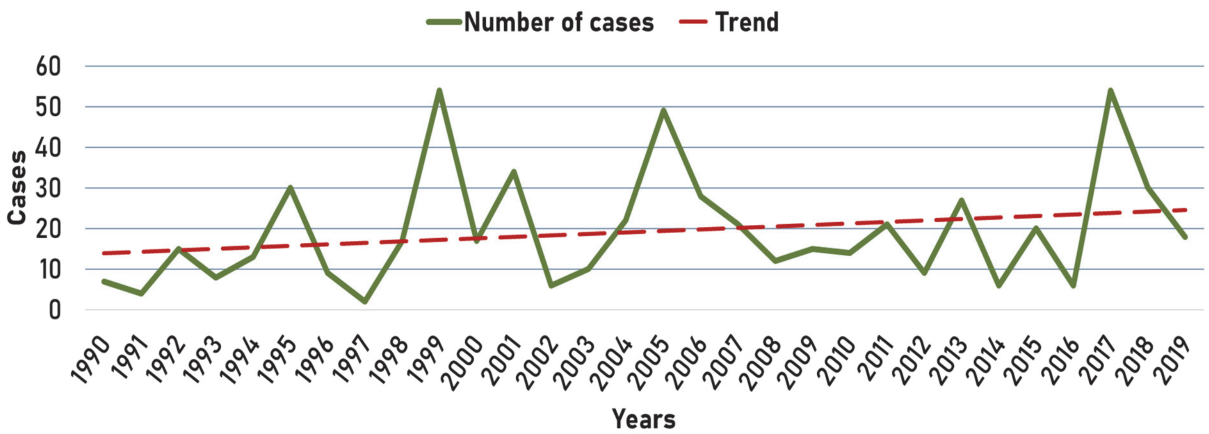

Fig. 2. Total number of cases of heavy and extreme snowfalls

As it can be seen from the graph (*Fig. 2*), the number of cases varies significantly from year to year. The most heavy and extreme snowfalls were recorded in 1999 and 2017 – 54 cases, and the least number was recorded in 1991 (4 cases) and 1997 (2 cases). In the first decade (1990–1999), 159 cases of heavy and extreme snowfalls were recorded, in the second (2000–2009) – 214 cases, and in the third (2010–2019) – 205 cases. The linear trend shows a tendency to increase the number of heavy and extreme snowfalls during the researched period, and therefore their recurrence and frequency increase. The same trends in climate change are observed globally (*Pachaury* and *Mayer,* 2014) and regionally (*Balabukh,* 2013). The average annual recurrence of heavy and extreme snowfalls happened in 19.3 cases, separately heavy snowfalls happened in 15.1 cases, emergency happened in 4.3 cases.

The average amount of precipitation that falls during one snowfall is of great practical importance. Calculations showed that for all cases of the studied snowfalls, an average of 26.6 mm of snow fell. The standard deviation was 7.7 mm, which indicates a fairly wide range of variation in precipitation during snowfalls. The coefficient of variation was 29%, which conditionally indicates the homogeneity of the sample and the rare recording of extraordinary snowfalls during which ≥50 mm of precipitation falls in ≤12 hours.

To calculate the climatic characteristics, the annual course of heavy and extreme snowfalls is important (*Fig. 3*).

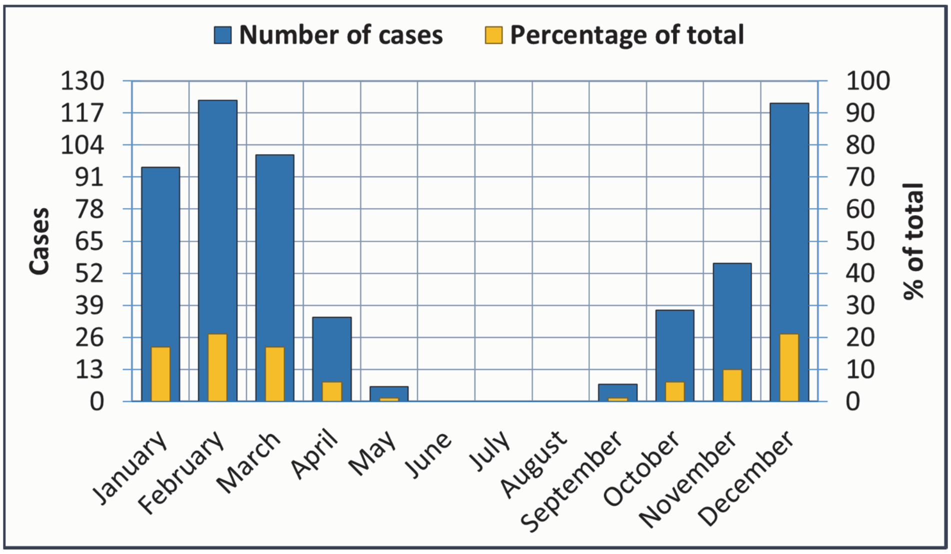

Fig. 3. Annual number of cases and their percentage of the total number of heavy and extreme snowfalls.

Analysis of the diagram (*Fig. 3*) shows that heavy and extreme snowfall fell during all seasons, except summer. Most of them were in winter: December – 121 (20.9%), January – 95 (16.5%), and February – 122 (21.1%) cases. A large number of snowfalls was recorded in March – 100 (17.3%) cases, which is due to the predominance of winter circulation this month. An interesting fact was that heavy snowfalls were observed even in May – 6 cases (1.0%) and September – 7 cases (1.2%), and during the warm period of the year (April-October), they were 14.5% of the total number of cases. The calculated average monthly distribution of cases is given in *Table 3*. Such distributions indicate the highest probability of heavy and extreme snowfalls in December and February, slightly lower in January and March, low in April, October, and November, and the lowest in May and September.

Table 3. The average monthly number of cases of heavy and extreme snowfalls

	Months											
	I	II	III	IV	V	VI	VII	VII	IX	X	XI	XII
Cases	3.2	4.1	3.3	1.1	0.2	-	-	-	0.2	1.2	1.9	4.0

The duration of snowfall is one of the most important characteristics. The process of snow accumulation and formation of snow cover height depends on it. During heavy snowfalls in the mountains of the Transcarpathian region, an increase in snow cover up to 50 cm can occur per day, which sharply increases the risk of avalanches (*Hryshchenko et al.,* 2013). The temporal dynamics of the duration of heavy and extreme snowfalls is given in *Table. 4*.

Table 4. Distribution of cases of heavy and extreme snowfalls of different duration

Duration											
to 1 hour	**1-2 hours**	**2-3 hours**	**3-4 hours**	**4-5 hours**	**5-6 hours**	**6-7 hours**	**7-8 hours**	**8-9 hours**	**9-10 hours**	**10-11 hours**	**11-12 hours**
Number of cases											
2	1	2	-	2	2	4	4	8	9	12	532

The uneven distribution of the duration of heavy and extreme snowfalls proves that in the territory of Transcarpathia, this natural meteorological phenomena are practically impossible to form, in a relatively short time interval (1–5 hours). However, the transience and discretion of snowfalls make it impossible to accurately record their duration, especially at night. Therefore, this conclusion is, to some extent, relative.

The spatial distribution of the researched snowfalls is of practical importance for the engineering design of buildings and structures, and other needs of various sectors of the national economy. For this purpose, the territory of Transcarpathia was mapped according to various indicators of distribution of heavy and extreme snowfalls. *Fig. 4* shows the general picture of the distribution of recurrence of heavy and extreme snowfalls during the researched period.

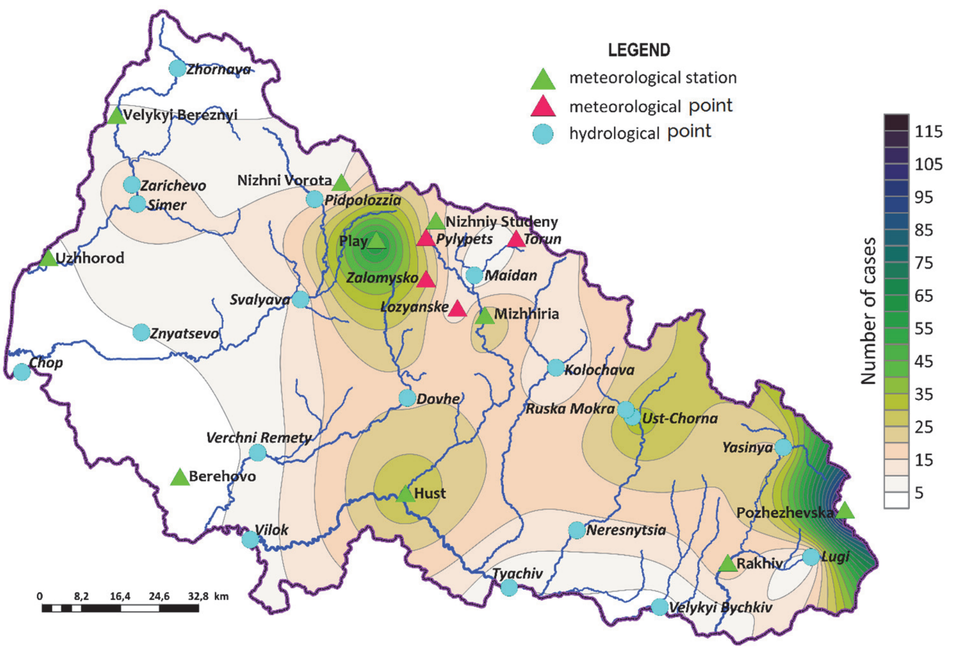

Fig. 4. Recurrence of heavy and constant snowfalls in Transcarpathia in the period of 1990–2019.

The map clearly distinguishes two zones of maximum recurrence: the territory of the mountain range Chornohora (snow avalanche station Pozhezhevska – 121 cases in 30 years) and the mountain range Borzhava (snow avalanche station Play – 62 cases in 30 years). Two more, less pronounced zones of significant recurrence are the upper left bank of the Teresva River basin (hydrological points Ust-Chorna – 34 cases and Ruska Mokra – 25 cases) and the catchment area of the Tysa and Rika rivers (meteorological station Khust – 31 cases).

The lowest recurrence is observed in the Transcarpathian lowland, which is part of the Middle Danube lowland (Uzhhorod aviation meteorological station – 3 cases, Beregovo meteorological station – 2 cases, and Chop hydrological point – 4 cases). Other zones of recurrence minima are the upper reaches of the Uzh River (Zhornava hydrological point – 1 case) and the estuaries of the Kosivska and Shopurka rivers (Velykyi Bychkiv hydrological point – 2 cases). In the rest of the territory, the recurrence rates, on average, vary from 10 to 20 cases over 30 years.

The next step was to map the quantitative indicators, i.e., the average and maximum values of precipitation during snowfall, recorded for each observation point (*Fig. 5*).

From *Fig. 5*(b) it is clear, that during one snowfall twice as much precipitation may fall as it is usually the case on average. In *Fig. 5* (a) the following zones of maximum precipitation values are distinguished: the upper parts of the Teresva, Terebli, and Rika river basins (Ruska Mokra hydrological point – 30.8 mm and meteorological points: Lozianske – 30.2 mm, Pylypets – 30.9 mm and Torun – 32.0 mm). It can be concluded that in these areas there are often extraordinary snowfalls, which are classified as natural meteorological phenomena of the highest III level of danger (*Table 2*). Areas of least risk of emergency snowfall are the right part of the Uzh River basin, the Verkhnyotysianska basin and the southern part of the Transcarpathian lowland.

Regarding the maximum amount of precipitation during snowfall (*Fig. 5* (b)), the distribution is slightly different. There are two distinct zones of maximum precipitation: the Borzhava mountain range and the upper reaches of the Teresva River. During the researched period, a record amount of precipitation during an extreme snowfall was recorded at the avalanche station Play (Borzhava ridge) on the night of January 18–19, 2007 – 71.3 mm/7 hours 10 min. Another zone of maximum precipitation is the ridge of Chornohora in the eastern part of Transcarpathia (avalanche station Pozhezhevska – March 4–5, 2001 54.3 mm/12 hours). Areas where extreme snowfalls have never been recorded are the upper right part of the Uzh River basin, the southwestern part of the Transcarpathian lowland, and the eastern half of the Verkhnotysianska basin.

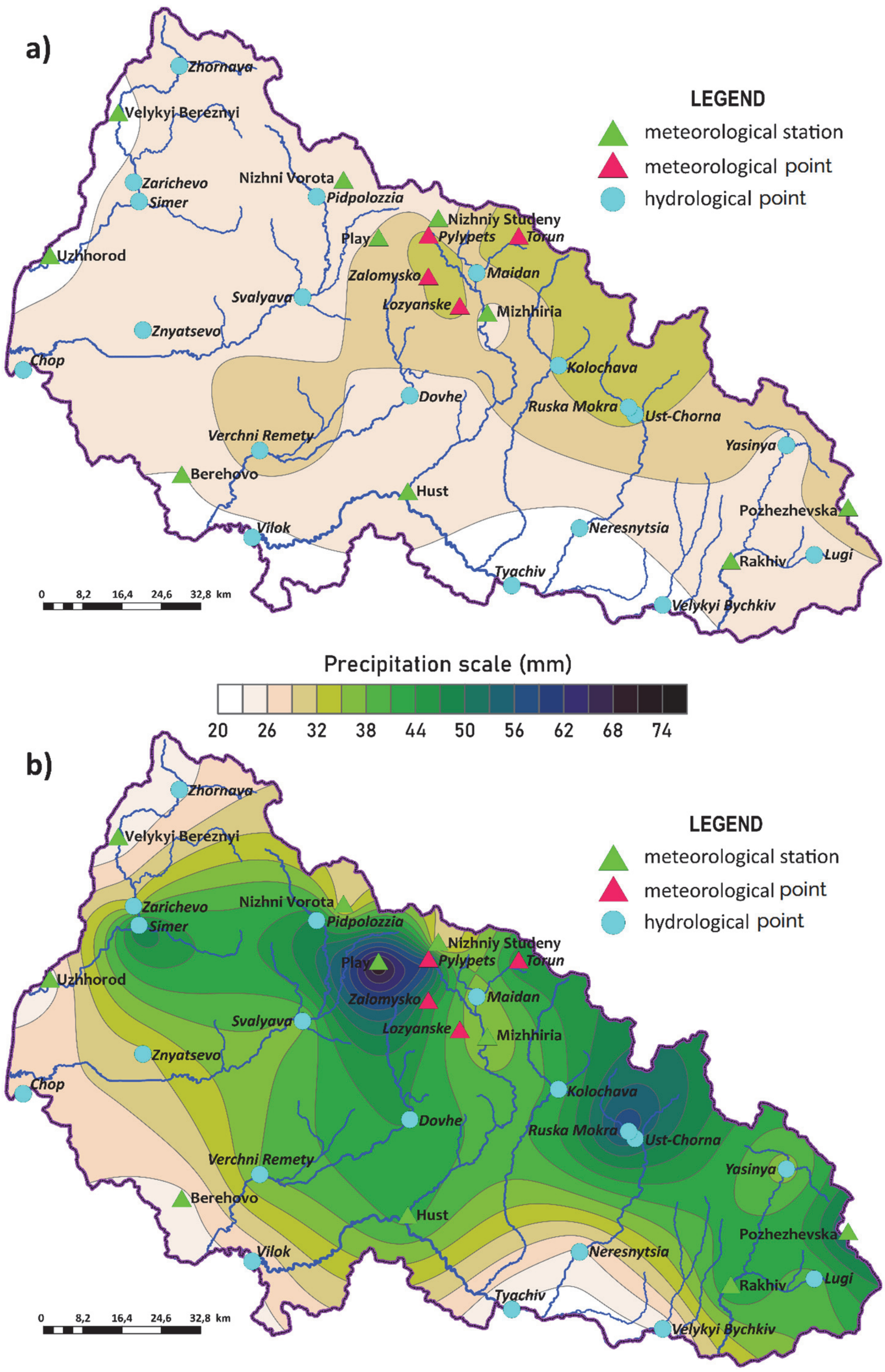

Fig. 5. Average annual (a) and maximum (b) precipitation of heavy and extreme snowfalls in Transcarpathia in the period of 1990–2019.

4. Conclusions

1. A positive trend in the number of heavy and extreme snowfalls in the Transcarpathian region for the period 1990–2019 has been identified. It is possible that in the future we should expect an increase in the number of cases of heavy and extreme snowfalls.
2. The average annual recurrence of heavy and extreme snowfalls during 1990-2019 was determined — 19.3 cases, i.e., on average, about 19 local cases of heavy and extreme snowfalls were observed in the Transcarpatian region a year.
3. When compiling the review of weather-forming processes, it is recommended to take into account the features of the annual course of the formation of heavy and extreme snowfalls, which has a maximum in February and December.
4. Over Transcarpathia, heavy and extreme snowfalls most often (92%) last 11-12 hours, falling 50 mm of snow in a shorter time interval is less likely.
5. The areas of the greatest natural load by heavy and extreme snowfalls due to mapping of the territory of the Transcarpathian region are selected – these are the territory of the Borzhava mountain range, the upper reaches of the Teresva River, and the Chornohora mountain range.
6. It is established, that the greatest recurrence of heavy and extreme snowfalls was observed in the mountainous part of the Transcarpathian region (on average 15–25 cases per year). The maximum amount of precipitation in the mountains during snowfalls varies between 25–35 mm. Extreme snowfalls, during which ≥50 mm of precipitation falls in ≤12 h, are a rare natural meteorological phenomenon.

For a more detailed study of heavy and extreme snowfalls as natural meteorological phenomena in the Transcarpathian region, it is advisable to conduct cluster analysis, and regression and correlation analyzes of their relationship with orography.

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