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Characteristics of Extreme Precipitation in Crimea

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Abstract

The paper considers the statistical characteristics of extreme precipitation according to long-term (75 years or more) measurements at 5 hydrometeorological stations in Crimea. Quantitative characteristics of the long-term variability of precipitation, the frequency of dry and wet periods, and the interannual variability of extreme precipitation are given. Cumulative distribution functions of extreme precipitation and their approximations based on generalized distributions of extreme values (GEV) are constructed. Both long-term averages and extreme precipitation values take its maxima at the Ai-Petri weather station. This station also has the longest wet periods (2.73 days) and the most intense daily precipitation (6.85 mm/day). The coastal stations of Kerch, Sevastopol and Feodosiya have the longest average duration of dry periods (up to 8 days in Feodosiya), and the total amount of precipitation in Simferopol is greater than that in coastal cities. The analysis of extreme precipitation confirmed that the most intense extreme precipitation is observed in the summer period on Ai-Petri (165 mm/day for a return period of 50 years), as well as in Kerch and Feodosiya. Extreme precipitation in Simferopol and Sevastopol is two times weaker than that on Ai-Petri.

Keywords: precipitation, Crimea, precipitation measurements, statistical characteristics, return period, return values

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Характеристики экстремальных атмосферных осадков в Крыму

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Аннотация
Рассмотрены статистические характеристики экстремальных осадков по данным долгосрочных (75 лет и более) измерений на пяти гидрометеорологических станциях Крыма. Приведены количественные характеристики многолетней изменчивости осадков, повторяемости сухих и влажных периодов, внутригодовой изменчивости экстремальных осадков. Построены кумулятивные функции распределения экстремальных осадков и их аппроксимации на основе обобщенных распределений экстремальных значений. Как среднемноголетние, так и экстремальные значения осадков максимальны на метеостанции Ай-Петри. В этом пункте также отмечаются наиболее продолжительные влажные периоды (2.73 сут) и наиболее интенсивные суточные осадки (6.85 мм/сут). В прибрежных пунктах Керчь, Севастополь и Феодосия отмечается наибольшая средняя продолжительность сухих периодов (до 8 сут в Феодосии), суммарное количество осадков в Симферополе больше, чем в прибрежных городах. Анализ экстремальных осадков подтвердил, что наиболее интенсивные экстремальные осадки отмечаются в летний период на Ай-Петри (165 мм/сут для периода повторяемости в 50 лет), а также в Керчи и Феодосии. Экстремальные осадки в Симферополе и Севастополе в два раза слабее, чем на Ай-Петри.

Ключевые слова: атмосферные осадки, Крым, измерения осадков, статистические характеристики, период повторяемости, возвратные значения

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Introduction

A characteristic feature of precipitation in Crimea is the significant heterogeneity of its distribution over the relatively small area. Most of the steppe region of the peninsula is characterized by insufficient wetness: the average annual precipitation makes 430–550 mm, while under the influence of the Crimean Mountains, much more precipitation falls in mountainous areas [1]. There, the amount of precipitation is approximately 1.5 times higher than that one over the steppe part of the peninsula. The extensive literature on the subject is devoted to the physical mechanisms of disturbances introduced by mountains into the wind and precipitation fields, e.g. [2–5]. At the same time, in the region of the South Coast of Crimea (SCC) – a narrow coastal strip along the southern slope of the Crimean Mountains – an area of subtropical (sub-Mediterranean) climate has been formed [6]. Despite the fact that the average annual precipitation here is close to the amount of precipitation in the steppe regions, most of it, as in the Mediterranean countries, take place during the cold winter period. On the contrary, in the domestic steppe areas of Crimea, the monthly variability is relatively small, with most of the precipitation taking place during the warm summer period [1)].

A remarkable thing of the distribution of precipitation is the decrease in the amount of precipitation in coastal areas compared to the central regions. For example, in Sevastopol, the average annual precipitation makes about 300 mm, while in Simferopol it makes approximately 500–700 mm [1)]. It is associated with the relative increase in the amount of convective precipitation during the daytime in summer [7] due to the contribution of breeze circulation [8, 9].

The absence of the adequate observational network, as well as insufficient spatial resolution of satellite measurements [7, 10], makes it impossible to study the spatiotemporal structure of precipitation and to assess the probabilistic characteristics of precipitation throughout the peninsula. First of all, such an assessment is very important for the cases of extreme precipitation, the catastrophic manifestations of which are most noticeable in some areas of the peninsula, namely, in mountain valleys and on mountain slopes [11].

One of the cases of heavy summer rain in the SCC region refers to September 6–7, 2018. In Yalta and Feodosiya, almost two to three monthly amounts of rainfall was measured. Two more recent extreme precipitation events refer to the summer of 2021. On the night of June 17, real tropical downpours, the largest ones in the last 100 years, came to Crimea, which had previously suffered from drought. Within a matter of hours, the amount of precipitation corresponding to the norm for 2–3 months fell. The next day, big water came to Yalta. The same thing that had happened in Kerch was repeated there, but on a larger scale.

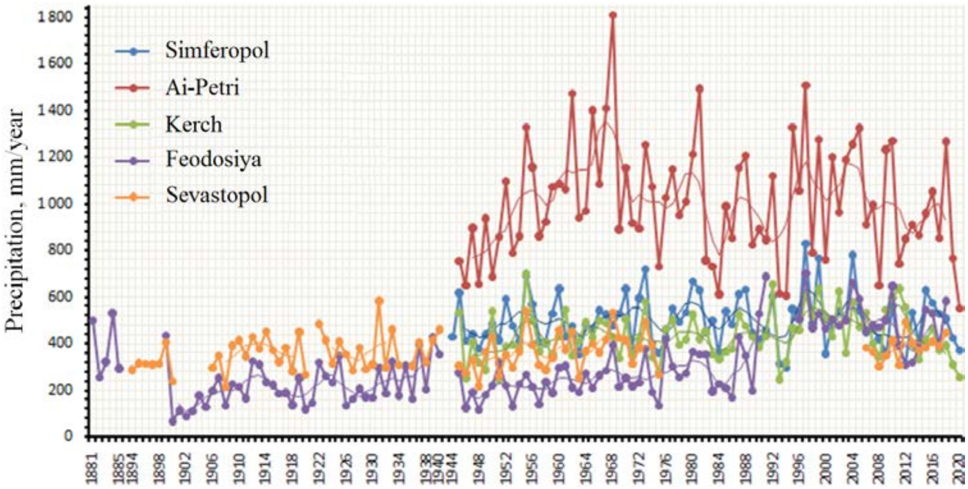
The purpose of this article is to evaluate the statistical characteristics of extreme precipitation, i.e. those exceeding the 99th percentile [12]. As pointed out above, there are very few long-term meteorological observations suitable for the assessment of the distribution functions and return periods of extreme precipitation in Crimea. The available dataset is comprised of archival meteorological measurements data collected at the hydrometeorological stations (HMSs) in Simferopol, Kerch, on Ai-Petri, in Sevastopol and Feodosiya for the period of at least 75 full years [2)], as well as the archives of the *RP5* website (URL: https://rp5.ru/). At all other locations of meteorological observations in Crimea, there are only fragmentary precipitation measurements available, while continuous measurements cover only the last 10–12 years and are not suitable for climate assessments.

Statistical characteristics of the series of daily precipitation at the meteorological stations of Simferopol, Ai-Petri, Kerch, Feodosiya and Sevastopol

Fig. 1 shows the time series of annual precipitation amounts at meteorological stations. Statistical analysis of these measurements showed that the largest amount of annual precipitation had been observed at the Ai-Petri meteorological station, located in the mountains. Here, the average annual precipitation amounted to 1,003 mm. In Simferopol, the average annual precipitation amounted to 499 mm, and at the coastal stations of Sevastopol, Kerch and Feodosiya, it was

1) Ved, I.P., 2000. [*Climate Atlas of Crimea*]. Simferopol: Tavriya-Plus, 118 p. (in Russian).

2) ECA&D Project Team. *European Climate Assessment & Dataset.* 2022. [online] Available at: https://www.ecad.eu [Accessed: 31.05.2022].



F i g . 1 . Annual precipitation amounts and the moving average over 5 points

significantly less and made 365, 437 and 299 mm, respectively. The interannual variability of precipitation amounts on Ai-Petri significantly exceeds the variability at other stations. The decrease in precipitation at all stations in 2019–2020 also calls attention to itself. In particular, the amount of precipitation on Ai-Petri was minimal during the period of interest, which was the main factor in the limited availability of freshwater resources in 2020–2021.

The precipitation series in Simferopol contains 28,125 measurements (77 years) with 18,890 days without precipitation. The precipitation series in Kerch and on Ai-Petri contain 27,759 daily measurements (76 years), while in Kerch there were 20,095 days without precipitation, and on Ai-Petri – 16,635 dry days. The series in Feodosiya consists of 42,733 measurements (111 years) with 34,480 dry days. In Sevastopol, the series contains 30,680 measurements (84 years) with 22,556 dry days. Averages values and maximum amounts of precipitation for the entire period of observations are given in Table 1. It also shows the average and maximum duration of wet and dry periods at meteorological stations and provides estimates of the intensity of daily precipitation, calculated by the following formula

$$P_{\text{int}} = P_{tot} / N_{wet} ,$$

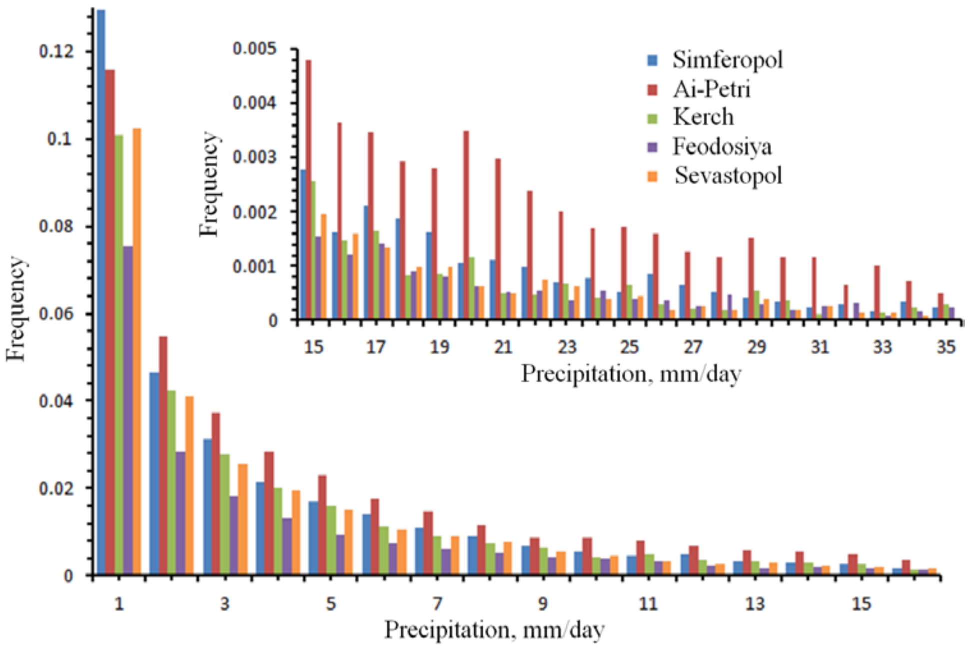
where P_{tot} – total precipitation amount, N_{wet} – number of wet days.

As could be seen, the intensity of daily precipitation is maximal for the Ai-Petri HMS, located on the top of the Crimean Mountains at an altitude of about 1000 m, and minimal for the Sevastopol HMS in the coastal southwestern part of the peninsula.

Histograms of daily precipitation series are shown in Fig. 2. In this case, the frequency or repeatability of the number of days with a given amount of precipitation is determined in relation to the total length of the series of observations. As is obvious, the repeatability of precipitation monotonically decrease with

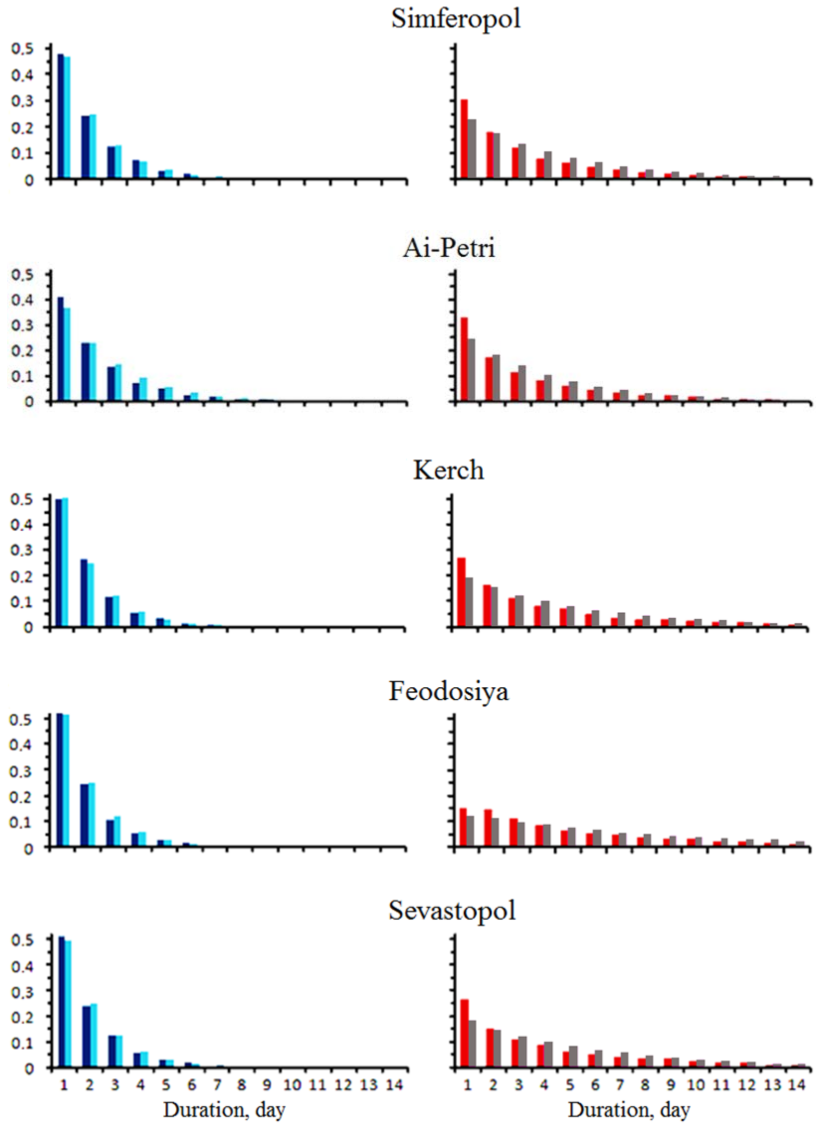
T a b l e 1. Statistical characteristics of daily precipitation series: all-time average daily precipitation P_{mean} (mm/day), maximum daily precipitation P_{max} (mm/day), average duration of dry periods $T_{drymean}$ (day), maximum duration of dry periods T_{drymax} (day), average duration of wet periods $T_{wetmean}$ (day), maximum duration of wet periods T_{wetmax} (day), precipitation intensity P_{int} (mm/day)

Weather station	P_{mean}	P_{max}	$T_{drymean}$	T_{drymax}	$T_{wetmean}$	T_{wetmax}	P_{int}
Simferopol	1.37	119.2	4.29	48	2.15	19	4.16
Ai-Petri	2.75	215.2	4.09	42	2.73	30	6.85
Kerch	1.20	300.0	5.18	57	1.98	13	4.33
Feodosiya	0.82	132.3	8.08	123	1.94	17	4.24
Sevastopol	1.00	209.0	5.57	60	2.01	15	3.78



F i g . 2 . Histograms of daily precipitation series at weather stations the increasing amount of precipitation for all the stations. Herewith, extreme precipitation is most frequent at Ai-Petri station.

An important characteristic of precipitation is the distribution function of dry days (i.e., days without precipitation) and wet days. Histograms of the periods of dry and wet days, as well as the probability distribution functions of the duration of dry and wet periods are shown in Fig. 3. For approximation, the following



F i g . 3 . Distribution histograms of the duration of dry periods and wet periods at weather stations (dark blue – empirical histograms of the precipitation period duration; light blue – approximation by geometric distribution; red – empirical histograms of the precipitation period duration; grey – approximation by geometric distribution) geometric distribution of the probability density [1)] was used

$$f\,(x_i = k) = p\,(1 - p)^{k-1},$$

where x_i – duration of wet or dry period; $p = 1/\bar{x}$ – distribution parameter, inverse number of average duration.

For all stations, the frequency of dry periods is approximately two times less than the frequency of precipitation periods; the most frequent are one-day precipitation periods and dry periods lasting 1–4 days. In 90 % of cases, precipitation lasts 3 days or less (4 days – on Ai-Petri), in 50 % of cases – 1 day. There are no significant differences in the duration of wet periods at different stations. At the same time, the frequency of one-day dry periods in Feodosiya is almost two times lower than at other stations, and long dry periods take place more often.

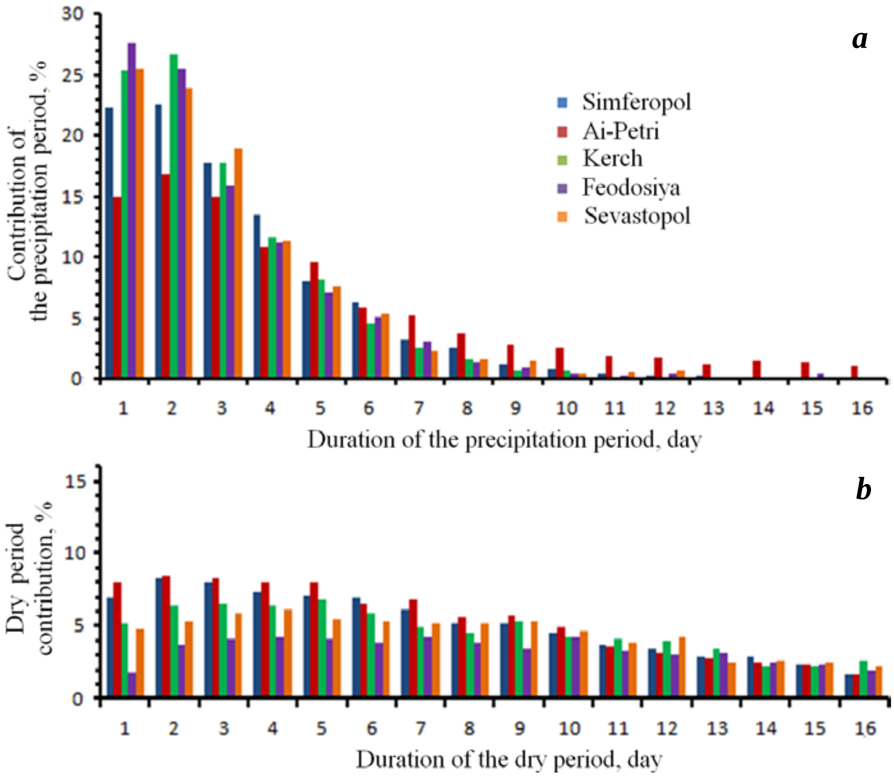
The distributions of dry and wet periods are important characteristics of the temporal structure of precipitation [13], which make it possible not only to judge the moisture regime of the region, but also to assess the possibility of droughts and floods. Indeed, even very heavy precipitation that fell within a short time is not as dangerous as relatively small precipitation falling over a long period. Such indicators as the contribution of wet/dry periods to the total number of days with/without precipitation are also important. Therein, the number of days is analyzed, that is, the proportion of days formed by periods of a given length, and thus the extremeness of the duration of periods of a given length is estimated.

Fig. 4 shows the proportions of periods of different durations to the total number of wet and dry days.

The relative contributions differ for the coastal and land stations. In Kerch, Feodosiya, and Sevastopol, dry periods of 10 days or more contribute more to the total number of dry days due to the reduced frequency of precipitation in summer. Vice versa, wet periods of 5 days or more make a smaller contribution to the total number of days with precipitation. Wet periods lasting 10–15 days take place on Ai-Petri.

Annual variation of extreme precipitation

The most intense extreme precipitation takes place in summer. Fig. 5 shows the amount of daily precipitation in Kerch and the annual variation of the average amount of precipitation exceeding the threshold value of 15 mm/day, which approximately corresponds to the level of 99% of the distribution function, as it will be clear from the subsequent. The maximum amount of daily precipitation, reaching values of more than 50 mm, falls on the summer period. Without giving the same distributions for the other four meteorological stations, it should be noted that they differ slightly from the distribution in Kerch, shown in Fig. 5. What can only be pointed out is that the summer maximum of daily extreme precipitation for Ai-Petri is less noticeable.



F i g . 4 . Empirical histograms of partial contributions of different duration periods to the total number of wet (*a*) and dry (*b*) days

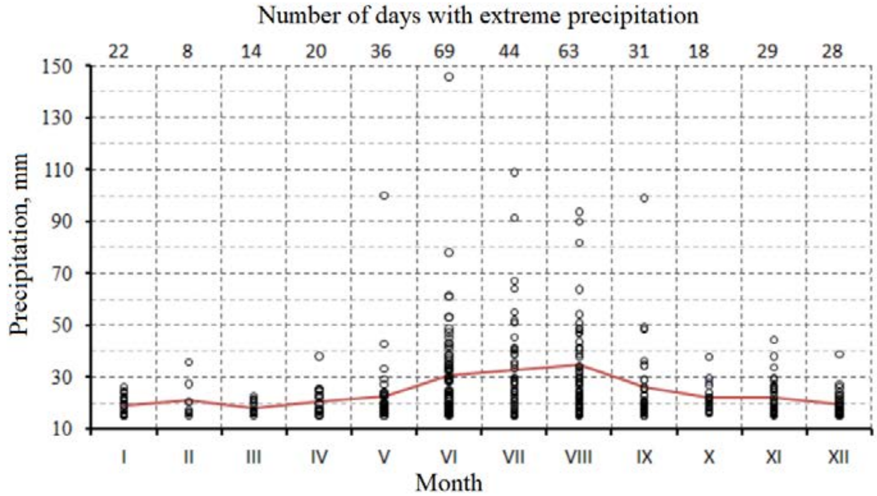
The explanation for the summer maximum of extreme precipitation is simple. Intensive precipitation in Crimea is caused by heavy rains associated with convective precipitation during the warm summer season. In winter, cloudiness that forms precipitation refers mainly to nimbostratus clouds. In this case, the source of moisture for continuous rains is the advection of water vapor as a result of transport from neighboring areas due to high airflow velocities [8]. Winter precipitation is long, but less intense and smaller in quantity.

Characteristics of extreme precipitation

To assess the probability distribution of extreme precipitation exceeding the selected threshold value, i.e., the tail of the full distribution function (usually from the value of 15 mm/day for the daily amount [14, 15]), the generalized extreme value (GEV) distribution is used. The distribution function of extreme values is given by the following formula

$$F(x;\ \mu;\ \sigma;\ \xi) = \exp\left(-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right),$$

where μ – location parameter; σ and ξ – scale and shape parameters respectively.



F i g . 5 . The monthly numbers of days with extreme (more than 15 mm) daily precipitation in Kerch according to measurement data for 1945–2020. The annual variation of the averages is shown in red

Fig. 6 shows the probability distributions of the daily precipitation series proper (cumulative distribution functions) and their GEV distribution approximation using the maximum likelihood method for five selected weather stations.

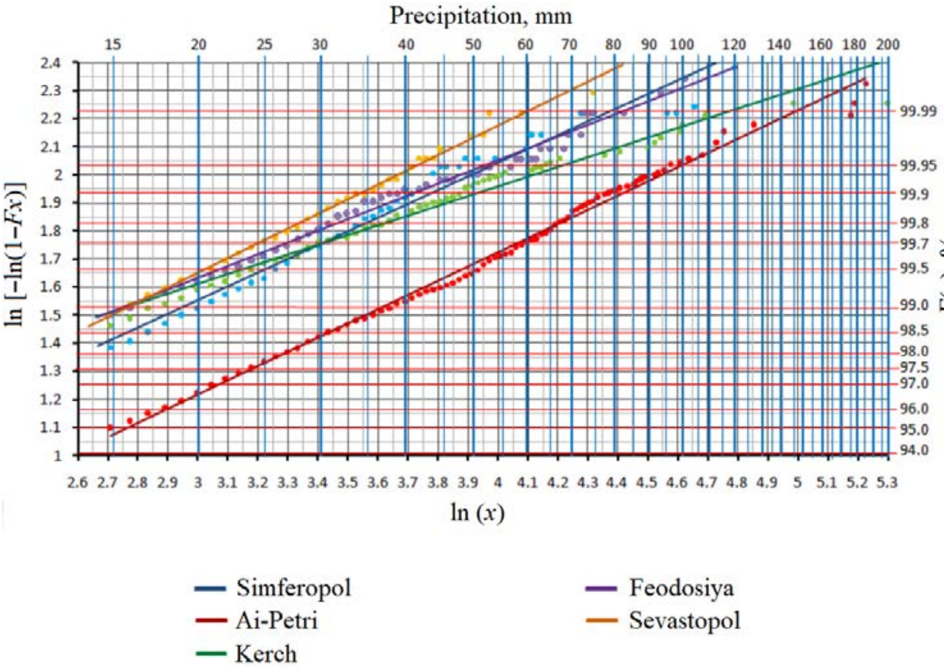
As is obvious, there is some difference between the distribution of extreme precipitation at Ai-Petri station and at other HMSs. For the former, the probability values are somewhat shifted towards lower values, i.e., higher values of extreme precipitation have higher probability, which is especially noticeable in comparison with Simferopol.

As an important characteristic of the precipitation absolute extremeness, the so-called return values (that is, values that occur once in a certain number of years) and return periods (that is, the waiting time for a given extreme value) are often used. Return values and return periods are related as follows

$$F_p = \left(1 - \frac{1}{\tau(R_p)}\right),$$

where F_p – estimate of the probability density (percentile) for daily precipitation return value R_p and waiting time of the event τ. In particular, for a return period of 100 years, the corresponding percentile would be calculated for a series of daily precipitation by the following formula

$$1 - \frac{1}{365 \cdot 100} = 0.99997 .$$



F i g . 6 . The probability density of daily precipitation (cumulative distribution functions) at weather stations in logarithmic coordinates and their generalized extreme values distribution approximation using the maximum likelihood method

From the percentile value, using the fitting distribution, it is easy to determine the return value for a given return period. The calculated estimates of extreme precipitation return values at meteorological stations for various return periods are given in Table 2.

T a b l e 2 . Daily precipitation (mm/day) at weather stations for various return periods

Weather station	Return period		
	20 years	50 years	100 years
Simferopol	70	85	98
Ai-Petri	137	165	190
Kerch	105	139	169
Feodosiya	76	96	113
Sevastopol	55	67	76

In general, the return values repeat the behavior of the precipitation intensity values. The highest values are accounted for the Ai-Petri HMS, the lowest ones – for the Sevastopol HMS. The physical reasons for this are rather clear, as the amount of precipitation in the area of high mountains is the highest one due to the peculiarities of the air flow around the mountains and increased condensation when the air rises to the top of the mountain. And the reduced precipitation intensity in Sevastopol compared to, e. g., Simferopol, as noted above, is explained by the influence of breeze circulation and the shift of the convective cloudiness formation area from the coastal to the land area during the day in the warm period of the year [7, 8]. All these arguments can also be confirmed by the calculated estimates of the maximum duration of dry and wet periods at meteorological stations for the return periods given in Table 3.

Table 3. The duration (days) of dry and wet periods at weather stations for various return periods

Weather station	Return period		
	20 years	50 years	100 years
Simferopol	34 14	38 16	41 17
Ai-Petri	32 20	35 22	38 28
Kerch	41 14	46 16	49 17
Feodosiya	67 12	74 13	79 15
Sevastopol	45 13	50 14	54 15

Note: above the line – duration of dry periods; below the line – that of wet periods.

Conclusion

The paper considers the daily precipitation measurements at the HMSs of Simferopol, Ai-Petri, Kerch, Feodosiya, and Sevastopol. Statistical analysis of the constructed series shows that the longest and most intense precipitation is observed at the Ai-Petri HMS, which is located in the mountains. The interannual variability of precipitation amounts is also higher there. At the coastal stations of Sevastopol, Kerch, and Feodosiya, the average annual precipitation, its intensity and interannual variability are much lower. In Simferopol, these estimates are in its mean range due to the more continental climate. They are somewhat higher than at coastal stations, but still significantly lower than at the Ai-Petri HMS. A similar pattern can also be traced with the assessment of dry and wet periods duration at these stations. The extreme precipitation takes its annual maximum in summer. This is explained by the fact that intense precipitation in Crimea is caused by heavy rains, which are formed as a result of atmospheric convection during the warm summer period. When assessing the probability of extreme values of precipitation, the GEV distribution was used, which made it possible to determine the return values of daily precipitation at weather stations for different return periods. In general, the ratio of return values is similar to the ratio of precipitation intensity values, as the highest values were obtained for the Ai-Petri HMS, while the lowest ones – for the Sevastopol HMS. The estimates of the dry and wet periods maximum duration given in the paper also follow this pattern.

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Contribution of the authors:

Vladimir V. Efimov – formulation and research task statement, preparation of the text of the article

Anatolii E. Anisimov – presentation of data in the text and their analysis, text editing

Olga I. Komarovskaya – calculations, preparation of graphic materials, text editing

All the authors have read and approved the final manuscript.