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INTERACTION BETWEEN CONTINENTAL WATERS AND THE ENVIRONMENT

Estimating the Probable Maximum Precipitation by Physical Methods Using Satellite and Radiolocation Observation Data: Case Study of the Middle Urals

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Abstract—The study considers the methods for evaluating the maximal possible daily storm rainfall (MPR) in the Middle Ural based on a combination of ground, aerological, satellite, and radiolocation data. The methods under consideration represent an alternative to statistical estimation approaches. MPR is evaluated using the total moisture content of cloud systems, described in terms of their stationarity or dynamics over time. The considered methods include evaluating moisture content based on the characteristics of vertical temperature distribution in the troposphere, convection rate, and the height of the upper cloud boundary. The estimates of the probable maximum precipitation, made for the conditions of stable or cloud-dependent moisture content, are comparable with the maximums evaluated by Hershfield statistical method. The probable maximums determined by physical methods are close to the values with exceedance probability of 0.01–0.001%, evaluated with the use of lognormal distribution. The method for evaluating the probable maximum precipitation can be used in engineering practice.

Keywords: probable maximum precipitation, maximum possible precipitation, storm precipitation, maximum precipitation limit, total cloud moisture content, convection rate, flood flow calculation, maximum possible runoff

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INTRODUCTION

The apparatus of mathematical statistics is used without alternatives in Russia and some other countries to calculate maximum possible total rainfall (MPTR) or PMP (Probable Maximum Precipitation) with different duration. However, the genesis of storm rains suggests the existence of physically based limit of total precipitable water (TPW) and the limit rate of liquid precipitation in different time intervals. This limit is determined by the specific features of climate in the regions under consideration, including the maximal height of the upper troposphere boundary (UTB), and the maximal convection rate in vertical development clouds.

The methods for MPTR evaluation have been described in detail in the modern studies and presented as practical recommendations [16, 22–24]. In most cases, the input parameters of the calculation models are the empirical data of ground or radiosonde observations. The introduction of radiolocation and satellite data into the practice of PMP evaluation is the topic of the recent decade; the methods for introducing such data in the estimation of maximum precipitation limits are now at the stage of development. This study gives methods for MPTR calculation based on physical methods with the use of parameters derived from data of a meteorological radar and a satellite. The obtained estimates of the maximum precipitation limits are compared with the results of calculation by Hershfield method.

The study area lies within the 200-km survey radius of Kol'tsovo meteorological radar (Yekaterinburg), which include several weather stations used by the authors in studying radar-based methods for evaluating storm precipitation rates [7, 8, 10–12, 20]. Earlier, the parameters of reduction of storm precipitation in the territory over time and area, as well as the characteristics of the distribution of the number of storms, the total precipitation, and the duration of events over the months of the warm season have been determined. The results of these studies were used in the article to transform the calculated maximum precipitation limits to unified time intervals.

AVAILABLE KNOWLEDGE

MPTR is the largest total precipitation over a period with specified duration, which is physically possible in a given geographic region in a given season [22]. This value has been used in the calculation of the probable maximal flood (PMF) since the 1950s, when methods for evaluating MPTR have been developed in the United States, China, India, and Australia [16, 21–24]. In Russia, estimates of MPTR have not been used.

The methods for evaluating MPTR known in the world can be divided into three groups.

(1) Group method based on the analysis of long-term observation series on storm precipitation at several points in a single geographic region. This group includes the well-known Hershfield method. The evaluation of MPTR by Hershfield method is based on constructing for a group of weather stations a regional relationship: $K_m = f\left(1/Cv_{n-1}\right)$, where Km is a factor to be evaluated for each time series of maximal daily precipitation in a year, Cvn–1 is a coefficient of variation of time series with a length of n – 1 (a time series with a length n, from which one maximal value is excluded). The value of Km is determined as

$$K_m = \frac{\left(X_m - \bar{X}_{n-1}\right)}{C_{vn-1}\bar{X}_{n-1}}, \tag{1}$$

where Xm is the first term in the ordered n-year precipitation observation series, i.e., the maximal value; $\bar{X}_{n-1}$ is the mean value for a series with a length $n - 1$, i.e., with the maximal value X_m excluded. For each station, MPTR (X_{PMP}) is determined by finding K_m from equation (1) for X_m, determined by the specified regional relationship, and parameters $\bar{X}_n$ and Cvn, determined, taking into account the observed maximum in the form: $X_{\text{PMP}} = (K_m Cv_n + 1)\bar{X}_n$. The number of weather stations involved in the analysis is not specified in [19, 22], but it should be enough for the construction of a regional relationship with a root-mean-square error not exceeding the measurement accuracy.

(2) The statistical method is based on the analysis of precipitation time series at observation points with the incorporation of various statistical distributions to evaluate the precipitation values of rare occurrence.

(3) The physical methods of MPTR evaluation are based on the genesis of moisture formation in clouds and assume the maximization of the total moisture content of the atmosphere, i.e., the evaluation of the coefficient of the ratio of the maximal observed (calculated) moisture content to its maximal possible value [22, 23], derived from the data of remote-sensing or aerological observations, or the estimation of moisture generation by convective clouds [2, 3]. The input calculation parameters for the analyzed methods are the vertical profiles of temperature and moisture content from the land surface to the cloud top (CT). The Hershfield method [19] is commonly used as an alternative to the other two methods.

The maximum limits, determined by some researchers by physical methods are close to the exceedance probability 0.01–0.001% [18, 21, 25].

The problem of calculation of the sums of heavy rain precipitation (the total precipitation within 12 h is in excess of 15 mm) based on data on the instability of convective clouds still has not definite solution in the world practice [1–3]. In Russia, the precipitation is evaluated using two global models, a regional model, several versions of WRF (Weather Research and Forecasting) model, a mesoscale model of the Hydrometcenter of Russia, and COSMO-Ru model (international Consortium for Small-scale atmospheric MOdeling in Russia). The main parameters for evaluating the instability are the height of the upper boundary of clouds and the actual moisture content, determined by radar data.

MATERIALS AMD METHODS

MPTR was evaluated using three sources of input data (instrumental data of ground and aerological observations, weather radar data, and satellite data).

The source data for the study were the data of aerological observations at weather stations Verkhnee Dubrovo and Ivdel over period 1934–2018, data of routine meteorological observations at weather stations of Yekaterinburg (1961–2018), Verkhnee Dubrovo (1961–2015), Zlatoust (1961–2018), Krasnoufimsk (1961–2018) and radar data (radio-echo height and cloud reflection power) with 30-min intervals at Kol'tsovo WR (2004–2017). To evaluate MPTR by Hershfield method, analysis was made of the observation series of daily precipitation maximums at 213 weather stations and gages of Ural'skii Department of Hydrometeoservice over the entire observation period (since 1880 to 2019) [8, 10].

The actual height of CT at the dates of falling of the showers that are maximized for the series of weather stations was determined based on data from three sources: satellite data (CTH or Cloud top height EDR Polar orbiting satellites CM SAF baseline area (30° N–80° N, 60° W–60° E); at a grid of 15 × 15 km), data on radio-echo height Kol'tsovo WR, and aerological data (aerological diagrams).

MPTR calculations were made with the use of two methods developed by WMO (evaluating the sum of storm precipitation at maximal moisture content of atmospheric column, TPW) and Hydrometcenter of Russia (the method for evaluating the maximal convective velocity in clouds of vertical development). Hershfield method was considered as an alternative to the two physical methods.

MPTR Calculation Based on the Total Precipitable Water (TPW)

In accordance with WMO procedure [4, 22], long-term series of routine observations of dew point temperature are analyzed to find the maximal value over 12 h over the observation period (in the case of 8-time observations, the maximal among the four continuous terms is taken). This value is used to determine TPW, and it is assumed that the entire moisture falls as precipitation. The long-term observation series of the routinely measured sums of showers over the entire period are analyzed to find the maximal value of total precipitation and the corresponding actual value of dew point, which is used to determine the actual TPW. MPTR is calculated as

$$P_{\max} = P_S \frac{\mathrm{TPW}_{\max}}{\mathrm{TPW}_S}, \quad (2)$$

where $P_{\max}$ is the maximal possible total rainfall (MPTR), mm; P_S is the total precipitation that fell during the observed maximal shower, mm (the largest observed precipitation sum over 12 h, i.e., within a single observation term in the case of two terms per day or the sum over 2 terms in the case of four terms per day); $\mathrm{TPW}_{\max}$ is the maximal possible water content of the atmospheric column at a point; TPW_S is the water content of the atmospheric column during the observed maximal shower. WMO publication [22] gives the values of moisture content of the atmospheric air contained between certain isobaric surfaces, depending on the dew point on the surface.

MPTR was calculated by WMO procedure modified by the author. Essentially, the modification consisted in that the height of the upper boundary of clouds was not specified arbitrarily, but was taken from a source, and the values of TPW in a cloud layer were not taken from tables [22], but were calculated using the vertical profile of the temperature and the dew point at the surface. This profile can be determined either based on radiosonde data or based on measurements of the radiation reflected by the land surface and upper cloud boundary, as well as the radiation absorbed by water vapor in the atmosphere with the use of active satellite sensors similar to RADAR [17]. Mathematically, the value of TPW_S (kg/m^2, mm, 1 kg/m^2 = 1 mm) of a column of atmospheric air of unit area can be determined by integrating the absolute air humidity over the vertical coordinate:

$$\mathrm{TPW}_S = \frac{1}{\rho g}\int_{P_1}^{P_2} q\,dp, \quad (3)$$

where q is absolute humidity, g/kg humid air layer; P_1 and P_2 are the heights of isobaric surfaces corresponding to the lower and upper boundaries of clouds, gPa; g is the acceleration of gravity, cm/s^2; ρ is water density, equal to 1 g/cm^3. In real showers, the rainfall often exceeds the estimated TPW. This is due to the convergence within convective cloud complexes [6]. Nevertheless, there exists a general correlation between the rainfall and the total moisture content.

The upper limit of troposphere moisture content can be determined by the absolute maximal height of its upper boundary (TUB). For the territory under consideration (Middle Ural), the maximal possible TUB height in July (in the period when extreme rainfall is forming) is 13.14 and its minimal height is 6.85 km [13]. The lower limit of moisture content is determined by the height of the lower boundary of clouds, which can be established either based on direct measurements of cloud height at weather stations, or by aerogram analysis.

A key characteristic in the calculation of the vertical profile of specific humidity is the dew point. The dew point temperature T_d on the land surface and in cloud layers was determined using the empirical formula derived by the author in analytical form based on a psychrometric plot:

$$T_p = \frac{233.77\ln\left(\frac{\mathrm{RH}}{100}\exp\left(\frac{16.57T-115.72}{233.77+0.997T}\right)\right)+115.72}{16.57-0.997\ln\left(\frac{\mathrm{RH}}{100}\exp\left(\frac{16.57T-115.72}{233.77+0.997T}\right)\right)}, \quad (4)$$

where T is temperature, °C; RH is the relative air humidity, %.

The cloudiness is determined in aerological diagrams by the minimal values of deficit T_p (commonly <3°) [15]. The absolute air humidity (g/m^3) in TPW calculations is determined based on humid air density by solving the Mendeleev–Clapeyron equation:

$$\rho_{\mathrm{steam}} = \frac{Mp_{(\mathrm{H_2O})}}{R(T+273.15)}, \quad (5)$$

where M is water molar mass, equal to 18.01528 g/mol; $p_{(\mathrm{H_2O})}$ is the partial pressure of water vapor in the air, gPa; R is the absolute gas constant, equal to 8.3144598(48) J/(mol K); T is temperature, °C.

The partial pressure of the gas mixture was calculated based on data on the relative air humidity φ and saturated vapor pressure p_{sat} as a function of temperature according to Magnus–Tetens equation:

$$p_{(\mathrm{H_2O})} = p_{\mathrm{sat}}\frac{\varphi}{100} = 6.112e^{\frac{17.67T}{T+243.5}}\frac{\varphi}{100}, \quad (6)$$

where T is temperature, °C; also, it can be taken from physchrometric tables.

Dry air density (kg/m^3) on an isobaric surface can be determined as

$$\rho = \frac{pM}{R(T+273.15)}, \quad (7)$$

where M is the molar mass, equal to 29 g/mol for dry air; p is absolute pressure, gPa; T is temperature, °C. From here, the absolute air humidity q is the ratio of water mass to the mass of dry air in the same volume, g/kg:

$$q = \frac{\rho_{\mathrm{steam}}}{\rho}. \quad (8)$$

Calculation of MPTR Based on the Rate of Convection in Cloud Systems

The input parameters for determining MPTR based on the rate of convection in clouds determined by RF Hydrometcenter procedure [2, 3] were experimental data of pluviographic observations of the rate and amount of precipitation and the data on the upper boundary of cumulonimbus clouds by the moment of precipitation start, measured with the use of weather radar (WR). The rate of precipitation $I(t)$ (mm/min) from large-scale cloud systems is determined according to [3]:

$$I(t) = 0.024 W_m \frac{\Delta t_s}{\Delta t}, \tag{9}$$

where W_m is the maximal convection velocity, m/s; Δt_s is the duration of a shower rain, min; Δt is the total duration of the rain, min. In accordance with [3], the convective cloud system includes clouds (cells), within which moisture generation is taking place (convective clouds), as well as other types of clouds, i.e., cloud moisture content is not constant over time. The coefficient of precipitation generation, which characterizes the ratio of the sum of actual precipitation to the total amount of moisture generated by the cloud, depends on the duration of the shower Δt_s and can be calculated as

$$k_0 = 0.0055 \Delta t_s. \tag{10}$$

At shower duration $\Delta t_s = 180$ min, which corresponds to the interval of meteorological observations; the coefficient of generation k_0 takes the value of 1. Assuming that, in the limiting case, the entire cloud system is convective and the shower duration is equal to the total rain duration ($\Delta t_s = \Delta t$), the maximal rain intensity can be found from (9) as

$$I(t = 180) = 0.024 W_m, \tag{11}$$

and the total precipitation, as

$$P(t = 180) = I \Delta t = 0.024 W_m \Delta t_s = 0.024 W_m \frac{k_0}{0.0055} = 4.36 W_m, \tag{12}$$

where $P(t)$ is the rainfall from the large-scale cloud system, mm.

The precipitation generation factor depends on the horizontal and vertical scale of cloudiness; it reaches its maximal values in the types of clouds may be related to the different size of convection cells typical of the clouds of cyclones and minimal values, in air-mass clouds [1]. Its different values for different types of clouds probably depend on the different sizes of the convective cells typical of the clouds from which precipitation falls. In the case of MPTR estimates, the coefficient of generation is taken equal to 1 (limit value).

The maximal velocity of convective flow in clouds over the period of radar observations was calculated using the following data: maximal radar reflectance dBZ (decibels with respect to Z; dimensionless logarithmic technical unit used in radar meteorology) in the survey radius of Kol'tsovo WR over period from 2008 to 2018 and the height of the top boundary of the radio-echo of cumulonimbus clouds H_m, km. The question of whether the observation period has been long enough is still open, requiring special studies, because in the overwhelming majority of cases, WR data in Russia are not available for researchers. The maximal convective velocity was calculated from (13) [14]:

$$W_m = 1.33[0.038 H_m (\text{dBZ} - 18) + 3.52] + 4. \tag{13}$$

The estimate of the convective velocity is in agreement with the values derived from the data of atmosphere radiosounding [1].

The total precipitation over 3 h P_{180} was converted into the maximal daily precipitation sums P_{1440} with the use of reduction relationships for precipitation rates over time [8]:

$$P_{1440} = \frac{P_{180}}{(180+1)^{1-n}} (1440+1)^{1-n} = 8^{1-n} P_{180}, \tag{14}$$

where n is an exponent characterizing the reduction of rainfall intensity as a function of its duration. The total precipitation over a noncalendar day (1440 min) was calculated for the conditions of the maximal observed duration of uninterrupted rain (with a rate in the central part of the shower >0.2 mm/min), taken equal to 1600 min for all weather stations in the Ural over 1936–2015 [11].

RESULTS

Of key importance in MPTR calculations is now the calculation of TPW, depending on the accuracy of determination of the limit height of CT. For the dates corresponding to the maximal sums of storm precipitation over 12 h, the values of CT were determined. Estimates of CT height for the showers under consideration are given in Table 1. CT height was evaluated by aerological diagrams based on the abrupt change of dew point deficiency over height (the symptom of cloud absence on the isobaric surface 550 hPa is the dew point deficiency >2.4°). CT was estimated by satellite data using the daily data of polar satellites; in the case where the data of Kol'tsovo WR over period from 2004 to 2018 was used, the evaluation was based on radio-echo height.

TPW in the atmosphere was calculated both based on WMO procedure [22] and by direct calculation of the vertical temperature profile using data of aerological, satellite, and radar observations. The results of calculations by WMO procedure are given in Table 2. The maximization was made for several largest precipitation totals over the observation period. The results are similar; however, it was shown that the lesser the

Table 1. Comparative characteristic of cloud height by satellite, radar, and aerological data

Date	Air temperature, °C	Dew-point temperature, °C	The height of the top cloud boundary, m		
			according to data of WR Kol'tsovo	according to data of polar orbital satellite	by aerological data
Verkhnee Dubrovo					
July 13, 2010	15.6	15.6	7000	6000	5600
June 13, 2014	20.9	15.0	7500	7200	6000
Yekaterinburg					
July 4, 2003	18.1	17.0	7000	6300	6000*
Aug. 5, 2007	22.0	18.2	9500	5000	5000*
Ivdel					
Aug. 1, 2013	14.9	13.8	n.d.a.	8000	5600
July 26, 2013	15.0	15.0	n.d.a.	6500	11300
Krasnoufimsk					
June 30, 2015	18.8	17.6	12000	8000	n.d.a.
July 15, 2011	16.5	16.2	8500	8500	n.d.a.

* According to Verkhnee Dubrovo weather station.

rainfall in the maximized shower, the higher the PMP estimate. This may be due to the decline in the correlation between the values of moisture content and the precipitation totals at a decrease in the latter.

In the calculation of the maximal convection velocity over 3 h, the height of clouds (radioecho height) was taken equal to UTB height, i.e., 13.14 km. The maximal recorded elevation-averaged radar reflectance in the zone of Kol'tsovo WR is 50 dBz (the limit value recorded by WR-5). In this case, the maximal possible convective velocity by (13) at the limit values of height TUB and reflectance is W_m = 29.7 m/s. At the same time, the limiting maximum of precipitation rate over 3 h in accordance with (11) for Yekaterinburg weather station $I(t)$ = 0.71 mm/min, and MPTR in accordance with (12) is 129 mm.

The conversion of three-hour rainfall to rainfall sums over a shower of any duration was made with the use of the results of the authors' studies of the maximal shower duration and the coefficient of shower reduction in the space. As it has been established by the authors in [8], an inverse relationship exists between the rain intensity over time intervals and their duration:

$$I(t)_{P,\%} = S_{P,\%}/(t+1)^n, \tag{15}$$

$S_{P\%}$ is the maximal (instantaneous) rain intensity at its duration $t \to 0$, depending on the exceedance probability of once in N years (the value of N is related with the exceedance probability P, %, by the formula $N = 100/P$); n is the same as in (14). According to the authors' studies, for the radius of Kol'tsovo WR (Yekaterinburg), n varies from 0.56 to 0.72. With calculated $I(t = 180) = 0.71$ mm/min, S takes values from 13.0 to 30.0 mm/min. Considering that $S_{P\%} = A + B\log(N)$ [8] (A and B are storm (rain) parameters constant for the chosen weather station; N is the same as in (15)), at specified storm parameters (e.g., $A = -1.55$ and $B = 3.58$ for Yekaterinburg), the exceedance probability $P_\%$, corresponding to the maximal intensity, is determined as

$$P_\% = \frac{100}{10^{\frac{S_{P\%}-A}{B}}}. \tag{16}$$

The maximal intensities and the daily precipitation sums in this case are close to the values with exceedance probabilities once in 1000–100000 years (0.1–0.001%). According to data in [8], the value of S varies from 9.36 to 15.1 mm/min. The maximal values of daily rainfall, calculated with the use of the observed intensity S_{obs} and the maximal intensity, determined by the rate of convection based on WR data S_{conv}, proved to be similar (Table 3). With the maximal convective velocity over 3 h assumed constant for the WR range, the maximal intensity of a shower and the total rainfall for the analyzed weather stations over time intervals of other duration will be different, because of the different values of A and B [8]. The results of calculations for the analyzed weather stations are given in Table 3.

DISCUSSION AND CONCLUSIONS

In the study, estimates of MPTR were obtained by two radically different procedures: WMO procedure for evaluating the total moisture content is based on the principle of its static character in the column of atmospheric air at maximal values of the height of the

Table 2. Estimates of the maximum precipitation limit by maximization of the limiting moisture content in atmospheric air column

Date GMT	Air temperature, °C	Relative humidity, %	Ground-level pressure, gPa	Height of the upper cloud boundary, m	*T* of the upper cloud boundary, °C	Dew point *T*, °C	Absolute humidity at the ground level		Estimated cloud moisture content, mm	Cloud moisture content by aerological data, mm	Rainfall, mm		
							g/m^3	g/kg			Actual over 3 h, mm	Estimated limiting maximum over 3 h, mm	Estimated limiting maximum over 24 h, mm
Verkhnee Dubrovo													
July 6, 1974	30.5	59	971.8	14000	–60.5	21.6	18.4	1.6	101	no precipitation*			
July 21, 1967	11.9	98	974.1	14000	–79.1	11.6	10.4	0.9	66	n.d.a.	85.4	131	301
July 13, 2010	15.6	100	970.6	8500	–39.8	15.6	13.3	1.1	55	34.4	36.9	115	266
June 13, 2014	20.9	69	966.7	8500	–19.9	15.0	12.6	1.1	29	31.0	47.9	196	451
Yekaterinburg													
July 2, 1981	28.8	69	972.6	14000	–62.2	22.5	19.6	1.7	113	no precipitation*			
July 22, 1983	13.3	96	967.4	14000	–77.7	12.7	11.1	0.9	70	n.d.a.	83.3	133	308
July 4, 2003	18.1	93	973.1	7000	–27.4	17.0	14.4	1.2	44	30.8	40.0	102	234
Aug. 5, 2007	22.0	79	983.2	4000	–10.0	18.2	15.3	1.3	27	35.6	25.8	109	251
Zlatoust													
June 23, 1985	26.5	81	951.5	14000	–64.5	23.0	20.3	1.8	115	no precipitation*			
July 13, 1966	14.7	94	950.2	14000	–76.3	13.7	11.8	1.0	71	n.d.a.	61.9	101	233
July 3, 1974	19.0	89	945.7	14000	–72.0	17.1	14.5	1.3	85	n.d.a.	51.0	70	160
June 9, 2006	15.7	95	955.4	6500	–26.6	14.9	12.7	1.1	34	n.d.a.	38.2	130	299
Ivdel													
Aug. 1, 1998	29.1	80	1007	14000	–61.9	25.3	23.2	2.0	137	no precipitation*			
Aug. 1, 2013	14.9	93	1001	12000	–63.1	13.8	11.9	1.0	60	35.7	74.5	171	394
July 26, 2013	15.0	100	993	9300	–45.5	15.0	12.8	1.1	51	29.5	47.9	129	298
Aug. 14, 1988	15.2	88	989	9150	–44.3	13.2	11.4	0.9	43	20.2	44.7	143	330
Krasnoufimsk													
July 24, 1971	30.9	72	997.2	14000	–60.1	25.3	23.0	2.0	131	no precipitation*			
June 19, 1973	16.6	96	986.9	14000	–74.4	16.0	13.6	1.1	84	n.d.a.	61.2	96	221
June 30, 2015	18.8	93	984.2	9500	–43.0	17.6	15.0	1.3	59	n.d.a.	36.9	82	189
July 15, 2011	16.5	98	984.8	5500	–19.3	16.2	13.8	1.2	34	n.d.a.	41.9	162	374

* The dates with comment no precipitation refer to the dates of highest dew point temperature at the ground within 12 h; in those dates, there were no liquid precipitation in the observation period.

troposphere and the dew point, while the approach of Hydrometcenter considers the air column as a dynamic system, in which processes of convection and convergence are taking place, also reaching limit values. The comparison of MPTR estimates over a day by the two methods shows that the daily maximums differ from one another by 9 to 33%. For the analyzed weather stations, MPTR estimates through convection velocity show higher values compared with those obtained by WMO procedure. MPTR determined by Hershfield method is 14–70% less than the values determined by WMO method (and, accordingly, less than the values calculated through the convection velocity). The values of MPTR calculated from (15) are similar to the statistically determined values of maximal daily rainfall with an exceedance probability of ~0.001% (Table 4). The maximal daily rainfall values with the exceedance probability of 0.001% were

Table 3. Calculated maximum precipitation limit at the maximal convection rate (the thick lines are division signs)

Weather station	Observation period of showers	Maximal observed shower intensity, mm/min	Maximal observed shower intensity $i(t)_{\max}$ (above the line) and the total precipitation (below the line) over time intervals, min		Shower reduction coefficient over time n (by MIG)	Shower characteristic of weather stations (by MIG)		Maximal convective velocity, m/s	Limiting calculated shower intensity, mm/min	Limiting calculated shower intensity (above the line) and total precipitation (below the line) over time intervals, min	
			180	1440		A	B			180	1440
Verkh. Dubrovo	1961–2014	14.4	$\frac{0.60}{109}$	$\frac{0.17}{245}$	0.61	–1.14	3.99	34.6	16.9	$\frac{0.83}{149}$	$\frac{0.23}{331}$
Yekaterinburg	1961–2015	13.0	$\frac{0.71}{129}$	$\frac{0.22}{320}$	0.56	–1.55	3.58	34.6	15.1	$\frac{0.83}{149}$	$\frac{0.30}{432}$
Zlatoust	1961–2014	13.3	$\frac{0.48}{85.9}$	$\frac{0.13}{182}$	0.64	–0.02	4.76	34.6	19.8	$\frac{0.83}{149}$	$\frac{0.22}{317}$
Ivdel	1961–2015	9.36	$\frac{0.22}{39.9}$	$\frac{0.05}{72.0}$	0.72	5.45	11.6	34.6	30.0	$\frac{0.83}{149}$	$\frac{0.19}{274}$
Krasnoufimsk	1961–2015	11.7	$\frac{0.32}{58.3}$	$\frac{0.08}{111}$	0.69	1.71	7.60	34.6	25.6	$\frac{0.83}{149}$	$\frac{0.20}{288}$

Table 4. Comparative characteristic of the maximum daily precipitation limits

Weather station	Observation period, years	Height, m	Characteristics of the largest annual daily rainfall by observation data and the exceedance probability $H_{0,001\%}$, mm				Calculated limiting daily rainfall, mm		
			Standard	C_v	C_s/C_v	$H_{0.001\%}$	by convection velocity	by TPW value	Hershfield method
Verkhnee Dubrovo	62	287	39.0	0.39	3.2	232	331	301	185
Yekaterinburg	63	281	36.8	0.45	2.3	203	432	308	264
Zlatoust	62	532	36.4	0.37	1.3	154	317	233	202
Ivdel	64	93	32.8	0.41	2.2	225	274	394	179
Krasnoufimsk	65	205	31.9	0.35	2.1	135	288	221	158

calculated with the use of lognormal (Captain) distribution, which gives the best approximation for the time series [12].

The classical Hershfield method is used in some studies abroad to compare MPTR estimates obtained by new methods; such comparison was carried out in this study. The analysis of the series of maximal daily storm rainfall within a year in the Ural from 213 weather stations in the operation area of the Ural Hydrometeoservice Department, Roshydromet, enabled establishing a relationship of the form $K_m = f\left(1/Cv_{n-1}\right)$, which has a coefficient of determination of 0.74. The obtained relationship was used to evaluate MPTR by Hershfield method (Table 4). The results of the study show the MPTR values obtained with the use of physical approaches to be higher than the estimates using statistical approach (Hershfield method), the difference reaching 40–50. In studies made in other countries, the differences between MPTR values obtained by different methods have different signs. Thus, in the case of China territory, MPTR estimates by Hershfield method were 1.5–2.0 times lesser than the values obtained by physical method [24]. A study for Malaysia [23] shows an inverse relationship (the values of MPTR obtained by Hershfield method were 1.7 times greater than those obtained by physical methods). This can be due to the specific climate features of the territories under consideration and the absence of consistent approaches to

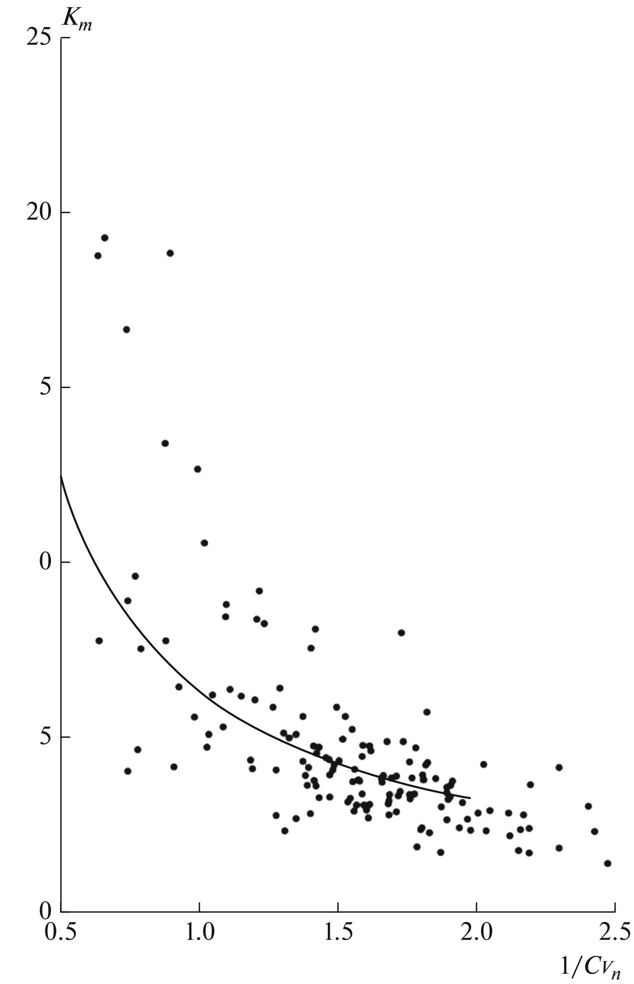

Fig. 1. The dependence of coefficient K_m on the ratio $1/Cv_n$ (for showers with duration longer than 1440 min).

the choice of duration of the observation period (in the presented study, periods with a duration of 25–100 years were used, embracing time series from 1880 to 2019; in the study [24], 15 years from 1998 to 2013; in [23], 10 years from 1974 to 1983, etc.). It is reasonable to suppose that for the estimates to be comparable, unified approaches to the choice of the length of observations are to be developed, and the duration can correspond to the generally accepted WMO recommendations with respect to the use of unified 30-year observation series for determining the statistical characteristics of climate (1931–1960, 1961–1990, 1991–2020) (Fig. 1).

As the essence of the physical method is the maximization of the rainfall sums (the determination of MPTR based on the actual maximum and the relationships between the limiting and actual maximal atmospheric moisture content) or the calculation of limiting convective velocities, it is necessary to carry out detail studies of the factors that determine the values of TPW of convective velocity.

The evaluation of TPW is a particular problem in the estimation of MPTR, the solution of which largely depends on the determination of maximal observed heights of cloud top (or the troposphere upper boundary (TUB)) and, hence, the temperature at this boundary. In this study, an attempt is made to coordinate the data on TUB height, obtained with the use of satellite, weather radar (WR), and aerological diagrams. The heights of TUB according to the two latest data sources are comparable with one another (Table 1). TUB heights based on WR data are close to the characteristics, derived from satellite or aerological observations, only near the radar, while the former become obvious overestimates with increasing distance from it. This effect is due to the refraction of radio beams at large distances from the radar in the upper atmospheric layers [14]. The limiting height of the upper boundary of moisture content is determined by the limiting TUB height: for the territory under consideration, this value is 13.14 km, while the height of the maximal observed upper boundary of clouds is 6.0–9.5 km. We have to assume that the minor amount of atmospheric moisture is contained in the stratosphere and mesosphere; however, there are no estimates of the involvement of these layers in the formation of storm precipitation.

The limiting value of the convective velocity (the velocity of vertical air motion) in clouds was found to be 34.6 m/s at limiting values of TUB height and the maximal observed (over the entire observation period, within the entire WR survey zone, and throughout the radio-echo height), radar reflectance (57 dBZ); similar values were obtained in studies [1–3]. As to the limit of radar reflectance, it should be noted that now it is determined by the technical potential of WR and cannot be in larger than 58 dBZ [14]. It is this limit that determines the calculation by the relationship (13). The maximal reflectance in the vertical profile of the cloud (in the height range of 4–6 km) corresponds to the transition zone of its phase structure from drop-type to ice-type and the formation zone of thunderstorm foci [3]. The calculation of the limiting convection speed is based on the condition that the mixed water–ice state corresponds to the entire vertical profile of the cloud, which is physically impossible. Therefore, although the issue of evaluating the limiting values of radar reflectance is now determined by the technical potential of WR, a more important problem of radar meteorology is the evaluation of integral reflectance characteristics in the vertical profile of a cloud. At the same time, this method of data collection for MPTR evaluation gives results close to other methods, methodologically differs from WMO method, and appears promising for further development.

MPTR estimate has more grounds in the physics of the process of atmospheric moisture formation; however, WMO method also has some modernizations taking into account the effect of convergence, the role of wind in showers, field estimates of the vertical profile of moisture content, etc. [24]. For example, according to data in [16], the value of MPTR over 24 h (PMP_{24}) by WMO procedure is determined from the relationship $PMP_{24} = 3.85 \times P_{50\%}-24.1$, where $P_{50\%}$ is the mean long-term daily precipitation maximum; with wind effect taken into account, it is determined from the relationship $PMP_{24} = 1.91P_{50\%}-20.3$. According to data in [16], taking into account the effect of wind makes MPTR estimates by WMO procedure closer to those by Hershfield method.

The further development of methods for MPTR evaluation, in the author's opinion, should include the development of methods for assessing the effect of landscapes on the physics of atmospheric processes, zoning of the territory by the conditions of precipitation, and the development of hydrodynamic models reflecting the processes of water cycle in clouds. In addition, the coordination of the calculated MPTR with the data of ground-based observations requires the development of the general principles of assessing the sufficient lengths of precipitation observation series, as well as methods for assessing the stationarity of series (including those grouped within homogeneous regions). It is also natural to incorporate nonmeteorological data (dendrochronological, paleoclimatic), which will improve the reliability of statistical estimates for the limits of physical variables of MPTR.

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