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**Preliminary Results of a Study of Steady  
Precipitation, Based on Data  
of a Dense Rain-Gage Network**

M.P. LEONOV

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PRELIMINARY RESULTS OF A STUDY OF STEADY  
PRECIPITATION, BASED ON DATA OF A DENSE  
RAIN-GAGE NETWORK

Translation of

Predvaritel'nye rezul'taty issledovaniia oblozhnykh osadkov  
po dannym gustoi osadkomernoii seti

by

M. P. Leonov

Kiev. Ukrainskii Nauchno-Issledovatel'skii Hidrometeorologicheskii  
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PRELIMINARY RESULTS OF A STUDY OF STEADY  
PRECIPITATION, BASED ON DATA OF A DENSE  
RAIN-GAGE NETWORK

by

M. P. Leonov

A method of investigation is presented and the properties of fields of steady precipitation are studied on the basis of the observations of a dense rain-gage network at the weather experiment range (WER) for six winter months of 1960-1962. The study deals with steady precipitation over the entire WER, the synoptic processes producing it, the optimum areas for averaging, the horizontal inhomogeneity of precipitation distribution on charts of semidiurnal and diurnal precipitation, and methods of smoothing the latter. The results should be applicable to studies of the physics of precipitation formation, evaluation of the effectiveness of experiments in seeding "raining" clouds, and computation of the amount of steady precipitation for any given area.

The horizontal distribution of precipitation on charts of semidiurnal and diurnal precipitation and on charts covering time intervals of a month or more is highly variable. In this respect, the summer rain showers that yield very large amounts of precipitation and the corresponding large horizontal inhomogeneities of precipitation distribution, have attracted special attention. Bogomazova and Petrova [1], Makhover [10], and Stout [16] have made such studies. To my knowledge, no such studies of steady precipitation for the cold part of the year have been made in the USSR.

Bergeron [17, 18] used data of a rain-gage network in southern Sweden to study the horizontal distribution of steady precipitation for several periods of the warm part of the year. Stout's paper [16], based on observations of dense rain-gage networks in Illinois, presents the most definite data on variations of precipitation with time and place. Although the author says that such observations were begun in 1949, he was able

to use only the three-year series of observations beginning with 1956, when the network was sufficiently dense and in steady operation.

Radar indicates that the structure of cyclonic precipitation is quite inhomogeneous, despite the common assumption that air currents in the winter cyclones are uniform over distances of several hundreds of kilometers. This cyclonic precipitation is described by Smith in [15] as ribbons, bands, and cells; he suggests that this short-range variability is explained by the properties of the air masses and the influence of the earth's surface. The observations at the WER yielded similar data.

#### 1. General Characteristics of Steady Precipitation at the Weather Experiment Range (WER)

The opportunity for studying this phenomenon in detail in the USSR has arisen only recently, in connection with the accumulation of information from dense pluviometric networks of runoff stations (Valday, Velikiy-Anadol', Zakarpatskoye, et al.), and especially since the dense network of stations was established at the WER. This pointed up the need for knowledge of the formation and distribution of steady precipitation. This information is required for evaluating the results of artificial modification of precipitating frontal nimbostratus, altostratus, and air-mass stratiform clouds (experiments in precipitation intensification), for improvement of hydrological calculations of runoff, and for providing agricultural organizations with more accurate information on precipitation amounts and snow depths.

The WER is located in the districts of Dnepropetrovsk, Kirovograd, and Nikolayev, and comprises two areas (test and control) that are 30 km apart. Each area is 70 x 50 km, with the long sides oriented along parallels of latitude. In 1963, there were 325 rain-gage stations in the test area of the WER and 314 in the control area. The stations are located at inhabited points, and thus are distributed irregularly over the areas, but the overall high density of the network insures sufficiently reliable data on precipitation distribution.

It is a laborious task to study precipitation distribution in individual showers on the basis of a dense rain-gage network. We developed a method for dealing with this situation and obtained preliminary characteristics of the horizontal distribution of steady precipitation that could be used to evaluate the cloud seeding experiments designed to intensify the natural precipitation [ 8]. The material consisted of charts of semi-diurnal (with some diurnal) precipitation for the test and control areas of the WER, arbitrarily chosen for individual showers; more exactly, these were charts for the above-mentioned periods, covering cases of liquid, mixed, and solid precipitation produced by the passage of cyclones and fronts over the WER, and sometimes by air-mass processes. The data cover six months of the cold season of the year (January, 1960, January, November, and December 1961, and January and February 1962).

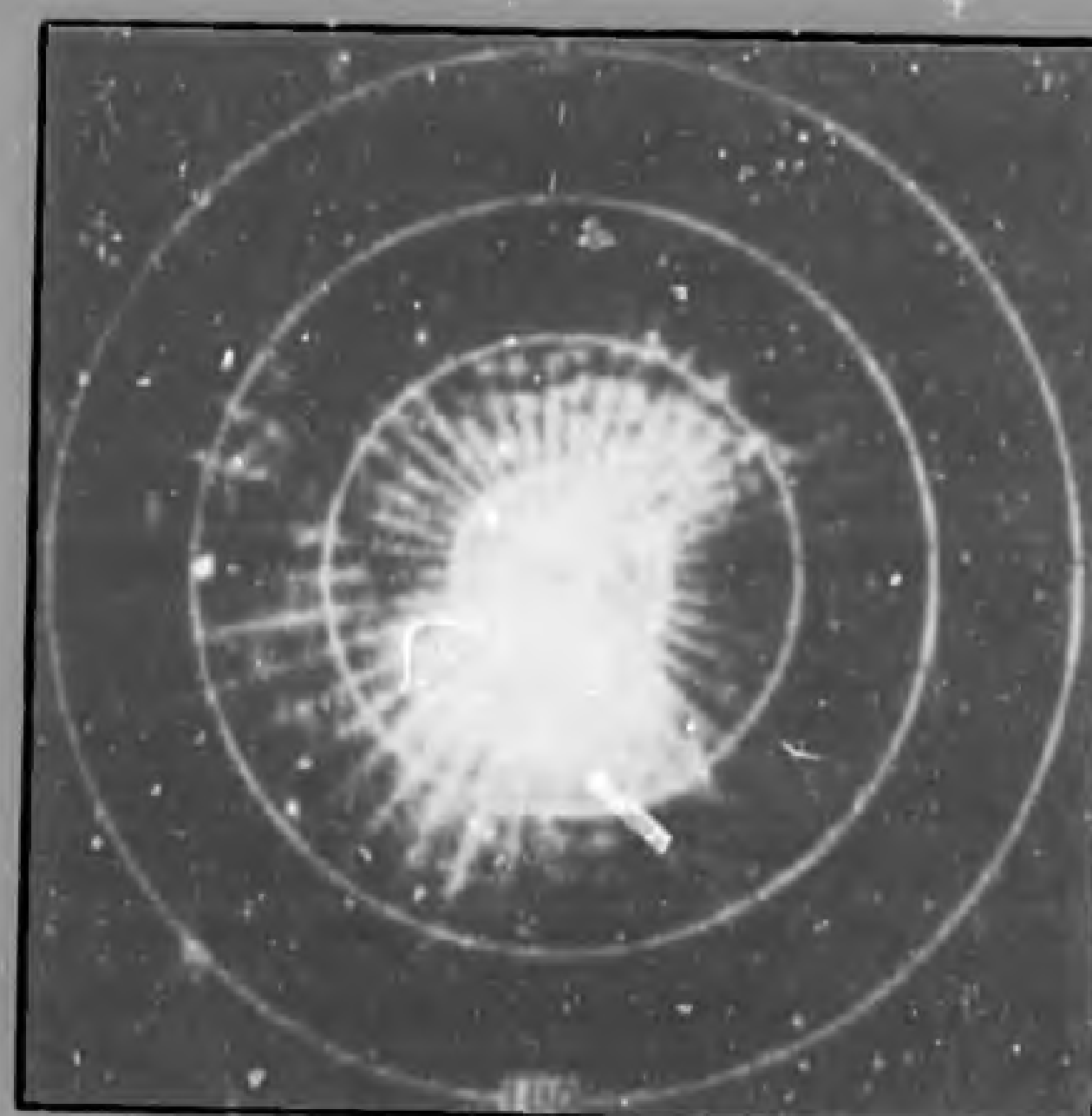


Figure 1. Radar scope, 1622: 26, 28 January 1962. The circles are 10 km apart. Centers of patches of intense precipitation can be noted at points with the coordinates:  $260^{\circ}$  - 27 km,  $290^{\circ}$  - 29 km,  $0^{\circ}$  to  $40^{\circ}$  - 15 km, etc. At distances greater than 35 km there was precipitation, but the radar did not "see" it.

The study included mainly cases where precipitation averaging more than 1 mm/12 hr fell on both areas of the WER, or covered one area completely. Forty five such cases (90 semidiurnal charts), plus 5 cases (10 precipitation charts) for 24-hr intervals, and individual charts showing average precipitation amounts of less than 1 mm/12 hr at the WER were analyzed for the test and the control areas. Charts of the monthly and seasonal precipitation totals for the same period, as well as other data, were analyzed.

Table 1 shows the types of synoptic situations in which steady precipitation was observed, as well as its frequency and the mean

precipitation at the WER areas for a given process. Steady precipitation was observed at the WER more than eight times a month: in most instances it was caused by the passage of cyclones and troughs (about 6/month). Such precipitation is frequently observed in gradient zones with fronts and rarely (but possibly) on the peripheries of anticyclones.

Table 1

Frequency of Synoptic Situations for Steady Precipitation at the WER, and the Corresponding Average Precipitation

Type of synoptic situation	Number of cases for period	Average semidiurnal precipitation at the WER, mm.
Central parts of cyclones, wave disturbances, and warm sectors	12	5.0
Back, cold parts of cyclones	3	4.1
Troughs:		
a) with warm fronts and occlusions	13	2.4
b) with cold fronts and occlusions	7	2.8
Gradient zones:		
a) with fronts	10	3.2
b) without fronts	3	1.8
NW and SW peripheries of anticyclones	2	1.8

The average precipitation for a half day at the WER was: for cyclones, 5 mm; behind cyclones, about 4 mm; other processes, 2.5 to 3.0 mm; only in gradient zones without fronts and in anticyclones was it somewhat less than 2.0 mm.

For the period in question, the maximum average precipitation at the WER was: 1) 14.8 mm for the central parts of the cyclones during the day on 13 January 1961; 2) 14.1 mm behind the cyclone at night on 9 January 1960; 3) 7.6 mm in troughs during the day on 8 January 1960, and 4) 8.5 mm in the gradient zones during the day on 9 November 1961. The frequency of precipitation by type (liquid, solid, or mixed) was computed from the available data first for the entire WER and then for the four most representative stations. The observations of stations Bobrinets, Krivoy Rog, Zhovtnevoye, and Loshkarevka, which are approximately the same distance apart, were used in both methods. For the entire WER, the precipitation was considered liquid or solid only if rain or snow, respectively, was observed at these stations, while any other combination of precipitation types was considered mixed. With the first type of calculation, the frequencies for the entire WER were: liquid, 32%, mixed, 40%, and solid, 28% of the cases (table 2). The amounts, averaged for the area, were: liquid, 3.9 mm; mixed, 3.6 mm; and solid, 2.1 mm. Liquid and mixed precipitation are equiprobable in cyclones, but solid precipitation is rarer (12% of the cases). In troughs, all three types are equiprobable, while in gradient zones the frequencies of the mixed and solid precipitation are the same, while liquid precipitation is rarer (20%).

It is clear from table 2 that steady precipitation for 12 hr in winter produces less than 2 mm in 45% of the cases and more than 4 mm in 28% of the cases, while precipitation of more than 6 mm is observed in only 15% of the cases.

Table 3 shows data on the frequency of precipitation for the second calculation method (by type of precipitation at the individual stations and by the minimum temperature observed during its fall).

A comparison of table 3 with the last column in table 2 indicates a considerably lower frequency of mixed precipitation at the individual stations than for the WER as a whole. Mixed precipitation at individual stations was observed in 15 to 20% of the cases, liquid in about 35 to 45%,

Table 2

Frequency (%) of the Average Steady Precipitation for the WER Areas, Classified by Type and Amount

Type of precipitation	Precipitation amount					Total
	<2.0	2.0-3.9	4.0-5.9	6.0-9.9	>10.0	
Liquid . . . . .	10	9	6	6	1	32
Mixed . . . . .	19	9	6	3	3	40
Solid . . . . .	16	9	1	2	—	28
Total . . . . .	45	27	13	11	4	100

Table 3

Frequency (%) of Basic Types of Steady Precipitation at the Four WER Reference Stations

Station	Type of precipitation	Temperature in degrees			Total
		< -3	-3. +3	>3	
Bobrinets	Liquid	—	18	10	28
	Mixed	2	14	4	20
	Solid	20	26	—	46
Krivoy Rog	Liquid	—	24	16	40
	Mixed	6	14	—	20
	Solid	8	32	—	40
Zhavtevoye	Liquid	—	36	10	46
	Mixed	6	18	—	24
	Solid	14	16	—	30
Loshkaevka	Liquid	—	30	16	46
	Mixed	2	12	—	14
	Solid	10	30	—	40
All stations	Liquid	1.5	27	13	41.5
	Mixed	4	14.5	1	19.5
	Solid	13	26	—	39
Total . . . . .		18.5	67.5	14	100

and solid in about 30 to 40%. Winter steady precipitation of the type considered falls mainly when the surface temperature is  $\pm 3^{\circ}\text{C}$  (67.5%), more rarely at temperatures below  $-3^{\circ}\text{C}$  (18.5%), and least often at temperatures above  $+3^{\circ}\text{C}$  (14%). In the last case, it is almost always liquid (93%), but at temperatures below  $-3^{\circ}\text{C}$  solid precipitation predominates (70%), though mixed (22%) and even liquid (8%) precipitation are possible.

## 2. Characteristics of the Precipitation Patches in the WER

Figures 2 and 3 are precipitation charts for 28 December 1961 showing the entire Ukraine and the control area of the WER, respectively. The typical feature of the precipitation field - its "patchiness" - is evident on both charts, but is shown in more detail by the dense rain-gage network of the WER. The patches are of two kinds: "positive," with higher precipitation values in the center than at the periphery, and "negative," with lower values in the center. As a rule, the patches are irregular ellipses; their dimensions can be determined approximately by the isohyets along the major and minor axes of the ellipses.

The patchiness of the precipitation, shown by the rain-gage network of the WER, is characterized by the number of positive and negative patches in each area of the WER, by their dimensions along the major and minor axes, and by the higher (for positive patches) and lower (for negative patches) precipitation values at the center of the patch than on its periphery (envelope isohyet). Both the positive and the negative patches form chains or complexes having their own envelope isohyets (fig. 3), but the study of the complexes is complicated by the indefiniteness of the contours of their envelope isohyets. Therefore, only the elementary formations shown in fig. 3 were considered in the calculations. The isohyets were drawn at 0.5 mm intervals everywhere. A patch thus outlined was included in the calculation if its existence was confirmed by two or more stations (or by the general path of the isohyets in a given section of the chart) and if its major axis was more than 3 km long.

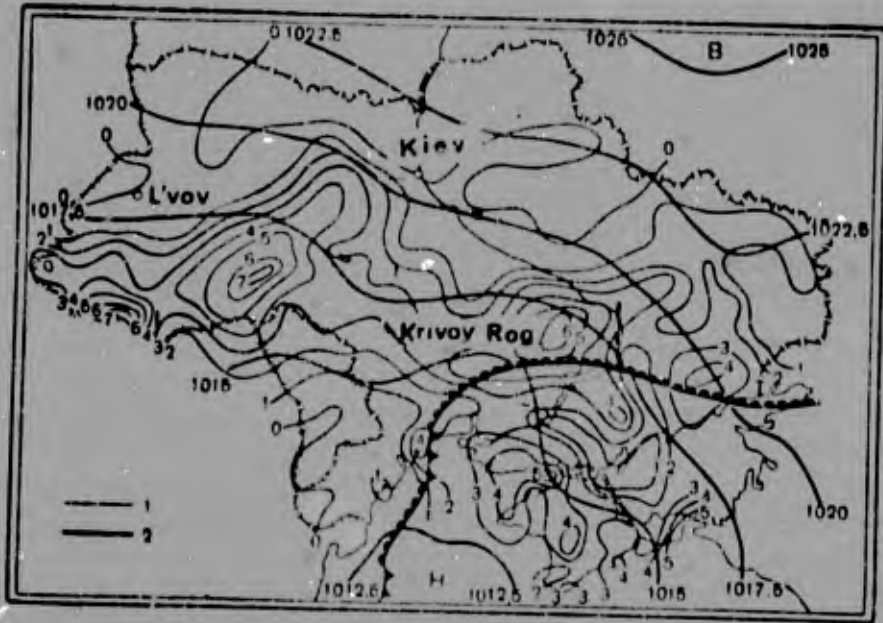


Figure 2. Synoptic chart of the Ukraine at 1200 LMT on 28 December 1961, and the daytime precipitation chart for that date.  
1. Isohyets, 1 mm intervals; 2. isobars, 2.5 mb intervals.

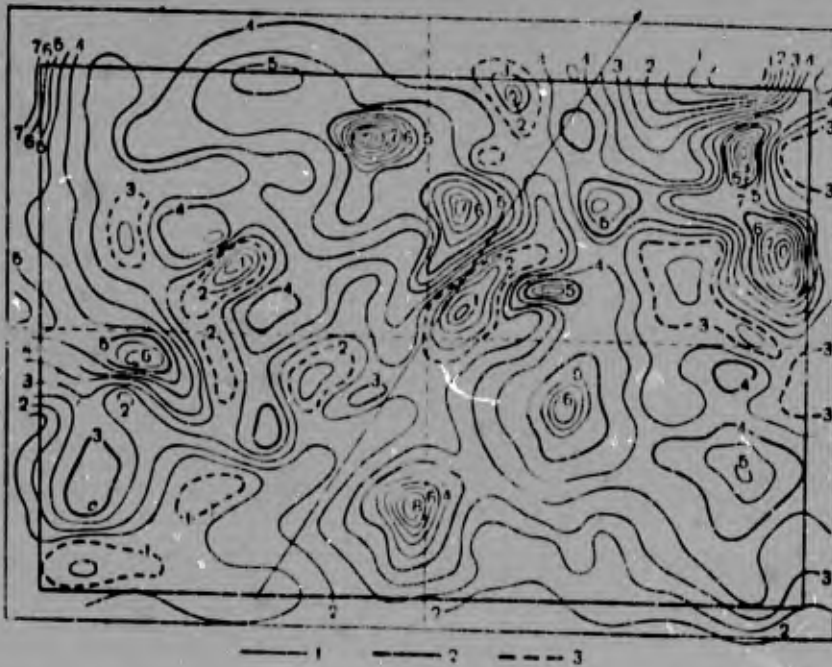


Figure 3. Precipitation chart of the control area of the WER, 28 December 1961.  
1. Isohyets, 0.5 mm intervals; 2. envelope isohyet of positive precipitation patches; 3. envelope isohyet of negative precipitation patches. The arrow indicates the mean wind direction in the cloud layer.

The calculations showed that on the average there are 12 to 13 positive and 10 to 11 negative patches in the WER. Thus, the average total for the area is 23 to 24 patches and the average area of a patch and the intermediate field of isohyets adjacent to it is approximately 160 km<sup>2</sup>. The zones of intensified precipitation in the test area varied between approximately 300 and 1300 km<sup>2</sup>, and were about 560 km<sup>2</sup> on the average, i. e., they were two to four times larger than the areas of the natural elementary precipitation patches.

Table 4

Frequency (%) of the Length of the Major ( $l_{\text{major}}$ ) and Minor ( $l_{\text{minor}}$ ) Axes of Precipitation Patches

		Length of axes, km									
		<4,0	4,1-6,0	6,1-8,0	8,1-10,0	10,1-12,0	12,1-14,0	14,1-16,0	16,1-18,0	18,1-20,0	>20,1
Positive patches											
$l_{\text{major}}$		9,2	26,1	22,2	16,8	11,1	3,5	3,5	3,0	2,5	2,2
$l_{\text{minor}}$		57,0	27,0	9,5	4,5	1,0	0,7	0,3	—	—	—
Negative patches											
$l_{\text{major}}$		7,0	21,5	22,0	17,0	10,0	10,0	5,6	2,6	1,5	2,8
$l_{\text{minor}}$		54,5	29,8	9,8	4,2	1,5	—	0,2	—	—	—
General (average)											
$l_{\text{major}}$		8,1	23,8	22,1	16,9	10,6	6,7	4,5	2,8	2,0	2,5
$l_{\text{minor}}$		55,8	28,4	9,6	4,4	1,2	0,4	0,2	—	—	—

Table 4 shows the frequency (in percent) of the various dimensions of precipitation patches in terms of the length of their major and minor axes for the WER. It is clear from table 4 that the size frequencies of the positive and negative precipitation patches are similar; therefore, it is more convenient to examine these data jointly. The average frequency data show that the major axes are predominantly 4 to 10 km long (62.8%), but the frequency of axes greater than 10 km is considerable (29.1%). The minor axes, as a rule, measure 6 km and less (84.2%), axes from 6.1 to 12.0 km being observed only rarely (15.2%).

Table 5 gives the frequency of the precipitation patches in question in terms of the difference in the precipitation at their centers and on the envelope isohyet (in terms of intensity).

Table 5  
Frequency (%) of Intensity of Precipitation Patches

	Difference between values at the center and on the envelope isohyet, mm								
	0.0-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	2.6-3.0	3.1-3.5	3.6-4.0	>4.1
Positive patches	32.2	31.6	17.1	8.4	5.0	2.4	1.0	1.1	1.3
Negative patches	61.0	23.0	8.4	5.2	1.6	0.8	—	—	—

It is clear from table 5 that the difference between the precipitation values at the centers of the patches and on the envelope isohyets is generally small, rarely exceeding 1.6 to 2.0 mm. There is a substantial difference between the frequencies of the intensities of the positive and negative patches: more than half of the negative patches (61%) have a difference of less than 0.5 mm and values greater than 3.0 mm are not encountered in them; in positive regions, a difference of less than 0.5 mm is observed in 33% of the cases, 0.6 to 1.5 mm in 48.7% of the cases, and more than 1.5 mm in approximately 19% of the cases. On the average, the value in the center of a patch is 1.0 mm higher than on the envelope isohyet for positive patches, and 0.5 mm for negative patches. Forty seven charts of the test (without artificial modification of the clouds) and control areas were used in the calculations. These charts showed 1062 patches: 597 (56.3%) were positive and 465 (43.7%) were negative. The greater average number of positive patches is natural: it reflects the process of their formation. The positive patches result from local intensification of precipitation against a general background of precipitation, while the negative patches are the intermediate

segments that are not always formed by closed isolines. The lower intensity of the negative patches also indicates this. On individual precipitation charts, the number of negative patches exceeded the number of positive ones in some areas of the WER, but this was not characteristic and in such cases, the negative patches were small.

A comparison of the orientation of the patches and groups of patches with the direction of the mean wind vector in the cloud layers for corresponding semidiurnal and diurnal periods shows merely a tendency toward elongation of the major axes of the patches ( $l_{\text{major}}$ ) downwind, but no clear link between these processes was detected. This is apparently explained by the large averaging intervals, within which specific patches of precipitation could form during different time intervals and wind directions.

The patchiness of the precipitation fields is also preserved in charts of their monthly sums. On these charts, with the same criteria for classifying precipitation, the yearly average was approximately 10 patches with higher sums and 7 patches with lower sums; in general, the number of patches varied from 3 to 14. The number of patches was somewhat smaller in the cold half of the year than in the warm half. The patches on the monthly charts varied from 4 to 30 km for the major axis (6 to 18 km in 84% of the cases) and 2 to 16 km for the minor axis (2 to 8 km in 37% of the cases). The ratio of the minor axis to the major varied within broad limits, with values from 0.21 to 0.60 (85% of the cases) prevailing. The pluviometric gradients on the charts of monthly precipitation were determined for the sections between the centers of the positive and negative patches. The values of the gradients thus calculated were as follows: from 1.0 to 3.5 mm/km (almost 80% of the cases) for the warm half of the year, and from 0.5 to 2.0 mm/km (60%) for the cold half. In individual cases, the pluviometric gradients could reach 10 to 11 mm/km in winter and 15 mm/km in summer. The latter reflects, even on the monthly charts, the predominance of the shower type precipitation.

By comparing the above data on the nature of the patches on the charts of individual showers with the patches on the monthly charts, we see that the latter are larger in size but fewer in number, i. e., the patchiness smooths out on the monthly charts. The larger pluviometric gradients are natural in this case, since the monthly charts show the precipitation sums.

### 3. The Average Characteristics of Precipitation at the WER

In using the data of the dense rain-gage network of the WER, the need naturally arises for averaging the observational data. This is done a) to obtain average precipitation values for each area as a whole or in part, b) to obtain the pluviometric gradients of an average field and to show the main trends of decrease or increase of precipitation amounts, and c) to find the optimum area for averaging.

The precipitation amounts for individual showers were averaged for the areas of the WER and their sections. The average precipitation amounts for individual periods (semidiurnal, or in individual cases, diurnal) were calculated from the isohyet charts for the test area as a whole and for the control area as a whole, and for quarters of these areas (outlined by the broken lines in fig. 3). By combined analysis of the isohyet charts and tabulated observations, we were able to eliminate many errors in the observational data and, in particular, to eliminate random (rough) errors. The average precipitation was taken from the isohyet charts at fixed points using a standard grid of 3-km squares (see fig. 6). 425 equally spaced points were selected in each area for convenient calculation. The average precipitation was also obtained by area from the observational data of the station network; there were no substantial differences between the values obtained by these two methods.

By such calculations we obtained the average precipitation for each quarter of the area shown schematically in fig. 3. Each of these

quarters of the WER is somewhat smaller than or is close to the average area of intensified precipitation in the modification experiments, and this served as the basis for determining the variability of the precipitation for just such an averaging area. From the average precipitation for each quarter of the area ( $\bar{R}_1$ ), we chose the maximum and minimum values ( $\bar{R}_{\max}$  and  $\bar{R}_{\min}$ ) and then found the difference ( $\Delta$ ) of the ratio of these values to the average value of each area ( $\bar{R}_{t[\text{est}]}$  or  $\bar{R}_{c[\text{ontrol}]}$ ) in percent. Half of the value obtained ( $\pm \Delta/2$ ) is taken as the characteristic of the relative variation of the average precipitation, viz., its deviation from the mean within the area for the case examined. The formula

$$\Delta = (\bar{R}_{\max} - \bar{R}_{\min} / \bar{R}_{\text{area}}) 100 \quad (1)$$

was used in the calculation.

The data for  $\bar{R}_{\max} / \bar{R}_{\text{area}}$  and  $\bar{R}_{\min} / \bar{R}_{\text{area}}$  are not shown because they are sufficiently symmetrical relative to  $\bar{R}_{t(c)}$  and  $\Delta/2$  can be determined from fig. 4. We see that variation by areas is great, especially for average precipitation of less than 0.5 to 1.0 mm, when  $\Delta/2$  reaches 100%, and for average precipitation of 2 mm or more, when  $\Delta/2$  is less than 50%, as a rule.

Figure 4 shows the relation of the average precipitation in the area ( $\bar{R}_{\text{area}}$ ) to its variation within the area ( $\Delta/2$ ). The distribution of points is such that in first approximation it is delineated by the hyperbola

$$xy = \text{const}, (xy = 2.45). \quad (2)$$

This means that the relative variation of the precipitation averaged by area is at most inversely proportional to its value, but generally this variation may be small for both heavy and light precipitation. An analysis of the synoptic conditions accompanying precipitation showed that the variations are larger on the edges of the precipitation zone and smaller in the central portions. Apparently the variation of  $\Delta/2$  may be

taken as a criterion of additional rainfall produced by artificial modification: the zone of intensified precipitation should coincide with  $\bar{R}_{\max}$  and in the case of artificial modification  $\Delta/2$  should lie near the hyperbola (fig. 4).

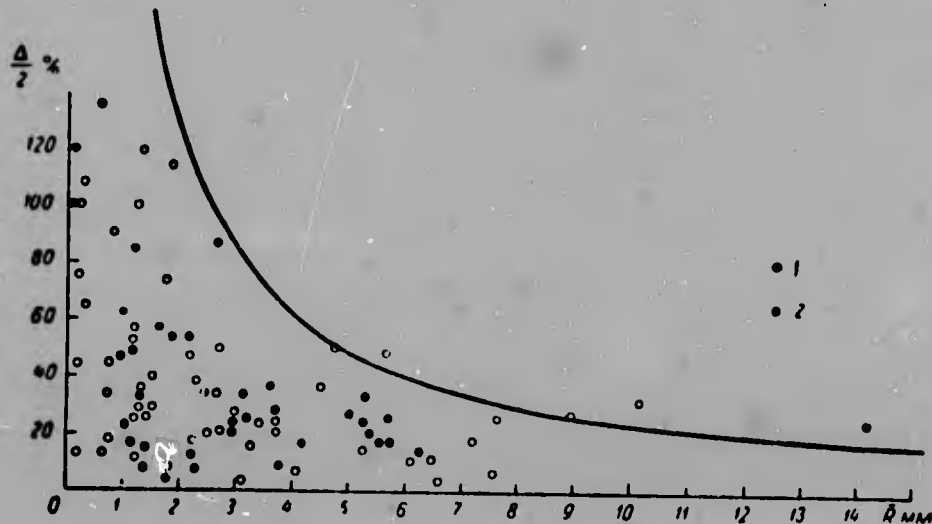


Figure 4. Relative variation of precipitation averaged over a limited area versus the average value for the entire WER.  
1. Average precipitation in the control area ( $\bar{R}_c$ );  
2. Average precipitation in the test area ( $\bar{R}_t$ ).

We studied the variation of the horizontal distribution of the average precipitation on the charts of monthly and seasonal sums in a similar manner. Charts of monthly and seasonal precipitation for the test and control areas for January-February and November-December 1961 and January-February 1962 were used for calculation (table 6).

A comparison of the data of table 6 and fig. 5 shows that the relative variation of the precipitation averaged by area decreases sharply when the time interval of their measurement is increased. The variation of the average monthly precipitation within the WER (table 6) was 8 to 27%, while it was 15 to 100% for individual showers (fig. 4). The variation was negligible (1 to 3%) over the entire interval (season)

studied (table 6). The relative variation of individual showers on the mean monthly charts is greater for light precipitation (e. g. , in the control and test areas in February 1961) and smaller for heavy precipitation.

Pluviometric gradients. One means of smoothing the observed inhomogeneity of the horizontal distribution of precipitation is to determine the pluviometric gradients of the averaged precipitation field. Apparently various directions can be chosen for such averaging. For example, the geographic directions of the horizon or the orientation of a front at the earth's surface may be taken as the basic directions. We calculated the components of the pluviometric gradients down and across the mean wind vector from the cloud top to the earth's surface. We used the same standard grid of 3-km squares we employed to determine the average precipitation by superposition on the isohyet charts of the WER area (see fig. 6), but this time oriented it along the mean wind, not along the sides of the area. The average precipitation for a field 3 km wide, oriented both downwind and crosswind, could then be calculated. The components of the gradients  $\partial \bar{R}/\partial n_x$  and  $\partial \bar{R}/\partial n_y$  were calculated from the mean values. Since the limits of the areas did not coincide with the wind direction, the number of averaged readings was not uniform: there were fewer at the limits (in the corners) of the areas, but in all cases at least 10 readings were averaged (a strip 30 km long), and this noncoincidence did not have a substantial effect on the results.

Profiles of the precipitation fields, averaged down and across the observed transport, were plotted on the basis of the data obtained. These profiles give an idea of the smoothed contours of the precipitation field (fig. 5). The average pluviometric gradients were determined by replacing the jagged lines by straight lines [ 5 ] drawn so that the areas thus formed were equal above and below the straight line. Figure 5 gives examples of large (28 December 1961, downwind,  $\partial \bar{R}/\partial n_x = 0.35$  mm/10 km) and small (14 November 1961,  $\partial \bar{R}/\partial n_x = 0.08$  and  $\partial \bar{R}/\partial n_y = 0.03$  mm/10 km)

Table 6

Mean Monthly and Mean Seasonal Amounts of Precipitation in the WER  
and its Variation Within Each Area

Month	Area	Average precipitation per area, in mm	From means for quarters of the areas,		Variation $\Delta/2\%$
			max, mm	min, mm	
January	Test	65.7	69.5	59.4	8
	Control	55.1	59.1	51.3	7
February	Test	8.9	11.1	7.7	19
	Control	10.6	13.0	7.3	27
November	Test	21.0	22.5	19.0	8
	Control	26.6	28.4	24.2	8
December	Test	31.3	35.1	29.8	8
	Control	21.6	26.1	18.4	18
		1962			
January	Test	18.5	21.3	16.3	14
	Control	13.9	16.4	11.4	18
February	Test	28.8	31.2	27.2	7
	Control	33.1	37.0	27.4	14
January, November, February, December 1961 and January, February 1962.	Test	174.2	177.7	166.9	3
Ditto	Control	160.9	162.1	158.4	1

average pluviometric gradients. The signs of the pluviometric gradients were determined by the direction of the normals, and directions with the flow ( $n_1$ ) and from right to left ( $n_2$ ) were considered positive.

The gradients examined are a good reflection of the basic features of precipitation distribution in each individual case: the rates of precipitation decrease grow from the average position of the cyclone center toward its periphery or from the average position of the trough axis (from the line of the front) toward its front or back.

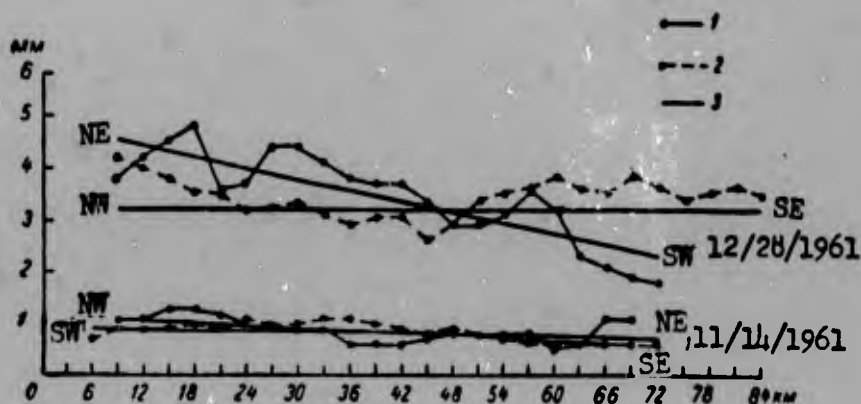


Figure 5. Profiles of precipitation fields averaged down and across the direction of transport of the precipitation-yielding clouds for large (28 December 1961) and small (14 November 1961) variability.

1. Downwind profile; 2. Crosswind profile; 3. smoothed precipitation profiles, from which the components of the pluviometric gradients of the averaged field were determined.

Table 7 gives the frequency of the components of the gradients of the averaged precipitation fields versus their values. It is clear from table 7 that in more than half the cases (56%) these gradients are less than 0.2 mm/10 km; in only 15% of the cases do they exceed 0.4 mm/10 km. The maximum value of such gradients was obtained for the heavy rain of 13 January 1961 ( $\partial R/\partial n = 1.14$  mm/10 km). Consequently, little variation appears in the averaged field of steady precipitation, but when distances

of several tens or hundreds of kilometers are involved (as in the case of artificial modification), these differences must be taken into account.

Table 7

Frequency (number of cases) of Components of the Pluviometric Gradients of the Averaged Precipitation Fields in the WER

	мм/10 км						Total	
	< 0,10	0,11— 0,20	0,21— 0,30	0,31— 0,40	0,41— 0,50	0,51— 0,60		> 0,61
$\frac{\partial \bar{R}}{\partial n_1}$	22	9	8	9	3	1	1	53
$\frac{\partial \bar{R}}{\partial n_2}$	15	13	5	9	4	2	5	53
Total	37	22	13	18	7	3	6	105
%	35	21	12	17	7	3	5	100

The precipitation chart of the control area (cf. fig. 3) clearly shows that the pluviometric gradients of the individual sections (in the patches) may exceed the values for the averaged field by several factors. The frequency of maximum gradients that characterizes the precipitation distribution in individual rains (table 8) is of particular interest.

Table 8

Frequency of Maximum Pluviometric Gradients in Individual Showers in the WER (winter of 1961 - 62)

	$\frac{\Delta R}{\Delta n}$ мм/км						Total
	< 0,5	0,51— 1,0	1,3— 1,5	1,6— 2,0	2,1— 2,5	2,6— 3,0	
Number of cases	4	16	11	6	3	3	46
% . . . . .	8,7	34,8	30,5	13,0	6,5	6,5	100

The gradients shown in table 8 were determined for each chart by averaging their four maximum values in the chart. This technique was used to smooth out possible distortions in the observations of the individual pluviometric stations. Inasmuch as the isohyets were drawn on the basis of interpolation and smooth out the features of the investigated field, the maximum gradients were determined not by the isohyets but between stations. This produced a slight deviation from the normals to the isohyets. Hence, it follows that the frequency of large gradients shown in table 8 is actually too low, but not much. In 65.3% of the cases, the maximum gradients for steady rain over the WER are 0.51 to 1.50 mm/km, but they can reach 3 mm/km and slightly more (1.6 to 3.0 mm/km in 26% of the cases).

Steady precipitation, measured on a semidiurnal or diurnal basis, extends for hundreds and thousands of kilometers, and although it is unequally distributed within such a region, it is heavier in its central part than on the periphery (see fig. 2). The average values obtained for the limited regions employed depend on the area averaged, therefore, one must determine the limits of the optimum areas within which the average values become quasiconstant. This is particularly important for evaluating the results of artificial modification.

The optimum areas for averaging the precipitation were determined by application of the grid of 3-km squares that was used to obtain the precipitation values from the isohyets (fig. 6). The middle square of the grid was taken as the origin and the averaging of values was extended in 3-km intervals, thus forming increasingly larger squares. Thus, for each precipitation chart nine average precipitation values were obtained corresponding to areas of 9, 81, 225, 441, 729, 1089, 1521, 2025, and 2601 km<sup>2</sup>, respectively (numbers of squares in upper left corner of each square in fig. 6). Here the differences between the averages are due only to the differences in the size of the territory.

These computations were made for 62 precipitation charts of both areas of the WER for cases when  $\bar{R}_{\text{area}} > 1$  mm for the corresponding

area and there was no artificial modification. The data obtained showed that the averages become quasi-constant beginning with averaged areas of 81 km<sup>2</sup> (53%) and 225 km<sup>2</sup> (47% of the cases).

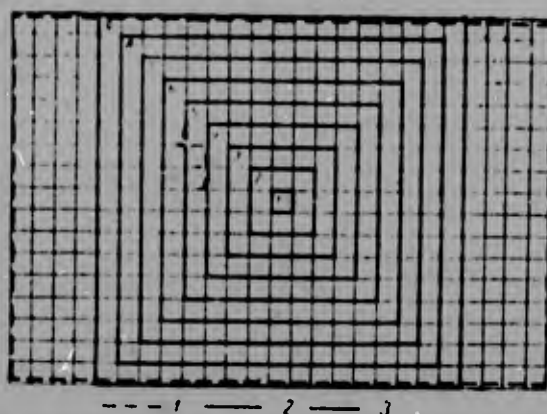


Figure 6. Diagram for obtaining the precipitation values from the isohyets of the areas of the WER.

1. Area boundaries;
2. grid of squares, from whose centers the averaged values were taken;
3. contours of areas averaged to determine the optimum averaging areas.

The gradations of the areas used (81, 225 km<sup>2</sup>, etc.) are relatively random (reflecting the method of the calculations), therefore, 100 to 200 km<sup>2</sup> can be taken as the lower limit of optimum areas for averaging. In averaging areas larger than 100 to 200 km<sup>2</sup>, up to the maximum area possible with the available data (2600 km<sup>2</sup>), the maximum differences between  $\bar{R}_i$  within the entire series did not exceed 1 mm in 87% of the cases, and comprised 1.1 to 2.0 mm in 11% of the cases (table 9).

Table 9

Frequency of Maximum Differences between Average Precipitation Values within the Optimum Areas of Averaging (areas greater than 80 to 225 km<sup>2</sup>)

	$\Delta \bar{R}_{\max}^{\text{mm}}$					Total
	<0,5	0,6-1,0	1,1-1,5	1,6-2,0	>2,0	
Number of cases	43	11	5	2	1	62
% . . . . .	69	18	8	3	2	100

No upper limit of the optimum averaged areas was discovered that could be considered the beginning of an abrupt or considerable change in  $\bar{R}_i$  with a further increase in area. This indicates that the optimum areas of averaging of steady precipitation extend more than 50 km in one direction. Let us note that large  $\Delta\bar{R}_{\max}$  were observed with large  $\bar{R}_{\text{area}}$  and, as a rule, with monotonically decreasing or increasing  $\bar{R}_i$ . A decrease of  $\bar{R}_i$  with an increase in the area of averaging was observed in cases where the center of the area coincided with the center of a precipitation zone for the corresponding period, while an increase of  $\bar{R}_i$  was observed when it coincided with a diffused periphery. Apparently cases of  $\Delta\bar{R}_{\max} > 1$  mm must be regarded as cases where there are no optimum areas of averaging. According to table 9, their frequency is approximately 13%. Within the optimum areas, the differences  $\bar{R}_i - \bar{R}_{i+1}$  did not exceed 0.5 mm. This value must also be regarded as the limit of accuracy of the amount of precipitation determined for a given territory.

#### 4. The Relation of Precipitation of Individual Showers, Measured at Hydrometeorological Stations, to the Precipitation Averaged over the Entire WER

The following steps were taken to determine the connection between the precipitation of individual showers and the precipitation averaged over the entire WER: a) the coefficients of correlation of  $\bar{R}_{t[\text{est}]}$  with the corresponding sums for the Air Weather Station at Krivoy Rog airport ( $R_{KR}$ ) and for Zhovtnevoye ( $R_Z$ ) were determined; b) the coefficients of correlation of  $R_t$  with the precipitation differences between the reference pluviometric stations of the same area were determined; c) the profiles of precipitation fields over the Ukraine were examined; these were constructed on the basis of the standard widely-spaced network of the Administration of the Ukrainian Hydrometeorological Service; d) the distribution of precipitation by stations of the test area was determined for moderate and heavy rain.

The correlation coefficients proved to be the same for 54 cases: 0.91 for Krivoy Rog airport, 0.85 for Zhovtnevoye. The equations of regression for these cases are

$$\left. \begin{aligned} \bar{R}_t &= 0.91 R_{KR} + 0.60 \\ \bar{R}_t &= 0.69 R_Z + 1.40 \end{aligned} \right\} \quad (3)$$

This example illustrates a characteristic feature of steady precipitation. The substantial horizontal variation of precipitation in individual showers is smoothed by using a large number of cases. The correlation of the precipitation at Krivoy Rog airport (western part of the area) and at Zhovtnevoye (eastern part) with the precipitation averaged over the entire area was practically identical.

The standard deviation  $\sigma$  for Zhovtnevoye was 3.4, while for Krivoy Rog it was 3.0, i. e., the scatter of the comparable values was considerable, but the inhomogeneity was smoothed out for a large number of observational data.

Assuming that there are stations in the WER which would distort the results, we selected seven of the most representative points in the test area and its periphery (Krivoy Rog, Zhovtnevoye, Loshkarevka, Nikopol', Naberezhnoye, Yevdokimovka, and Mar'yevka). Employing these, we determined the greatest variability (differences) of the precipitation amounts ( $\delta R_t$ ) for each rain, compared with the average precipitation for the whole area. We found that the differences in the amounts of precipitation  $\delta R_t$  at the representative stations for a territory not exceeding the dimensions of the WER are of the same order as the average precipitation amounts for the test area  $\bar{R}_t$ . The differences at these stations increase with an increase in the amount of precipitation. The average precipitation for the examined semidiurnal and diurnal periods was 3.0 mm; the average variation between the representative stations was 3.3 mm. The correlation coefficient between  $\bar{R}_t$  and  $\delta R_t$  is 0.75,

while the standard deviation is 2.53. The equation of regression for this case is

$$\delta R_t = 1.07 R_t + 0.11 \quad (4)$$

The analogous variation of natural precipitation, according to the data from a standard network of weather stations of the Ukrainian Hydrometeorological Service, is given in fig. 7. Precipitation profiles for a strip about 150 km wide (Chernigov - Kremenchug - Nikopol' - Melitopol' - Berdyansk) are given for the daytime measurement periods on 14 and 30 November 1961.

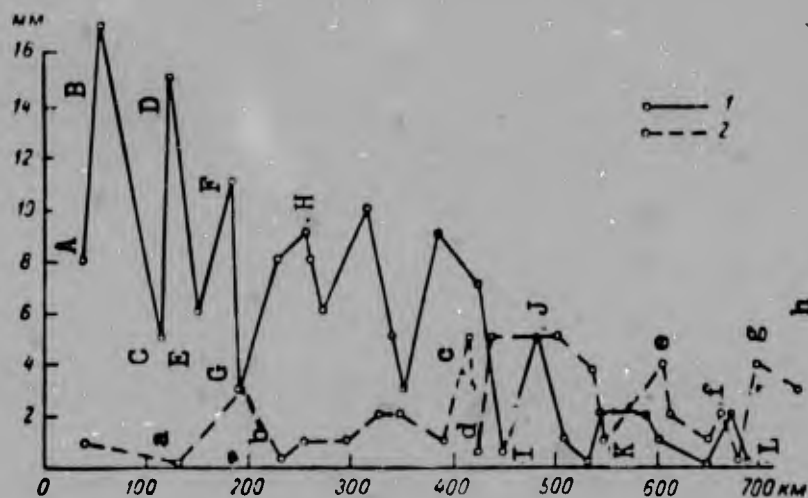


Figure 7. Precipitation profiles ahead of warm fronts, according to the sparse network of synoptic stations along the line Chernigov-Kremenchug-Nikopol' - Melitopol' - Berdyansk.

1. 2000 LMT, 14 November 1961; 2. 2000 LMT, 30 November 1961.

A. Chernobyl'; B. Chernigov; C. Kiev; D. Nezhin; E. Borispol'; F. Priluki; G. Yagotin; H. Zolotonosha; I. Krivoy Rog; J. Dnepropetrovsk; K. Dnepropetrovsk; L. Zhdanov.

a. Chernigov; b. Nezhin; c. Znamenka; d. Kremenchug; e. Nikopol'; f. Prishib; g. Melitopol'; h. Bot'yevo.

In both cases, this area was located ahead of warm fronts of western cyclones, whose centers were located northwest of the Ukraine. In fig. 7, although precipitation tends to decrease from NW-SE, i. e., toward the peripheries of the cyclones, the jumps in values at adjacent stations are very large. Thus, the data in fig. 7, which are completely representative, lead to the same conclusions that were obtained by analysis of precipitation charts of the WER compiled from the data of less qualified observers. This confirms the quality of the pluviometric observations of the WER network.

It is desirable to know the distribution of precipitation as measured by the stations in each section of the WER during the passage of fronts and cyclones. However, in this case, instead of using the direct station observations (owing to the variation in the number of operating stations), it was more convenient to use the precipitation values taken from the isohyets of charts of the standard network of 425 points (fig. 6). The frequency of the observed precipitation amounts was determined for each shower in the individual areas in 1 mm intervals. The shape of the curves of distribution was similar for all cases where the averaged amount of precipitation for the area  $\bar{R}_{\text{area}}$  was 2 mm and more, but owing to the differences in absolute values, simple averaging of the curves might have led to distortions. Therefore, the average precipitation values for the area  $\bar{R}_{\text{area}}$  were taken and then the distributions of the relative values  $R/\bar{R}_{\text{area}}$  were determined. The mean distribution curve constructed in this manner, on the basis of 51 cases for the test and control areas, was close to the curve of normal distribution of random values (fig. 8).

The curve of precipitation distribution with artificial modification (2) differs substantially from the curve without modification (1). The frequency of values close to or somewhat larger than the arithmetic mean increases noticeably in the case of modification, i. e., the precipitation values are higher for the most part when modification is employed. The aspect of the average curves of precipitation over the WER with and without modification clearly reflects the distributions observed in the individual cases employed in the averaging.

Thus, the distribution of steady precipitation, both moderate and heavy, follows an almost normal law of distribution with some asymmetry toward the smaller amounts. Employing the graph of the

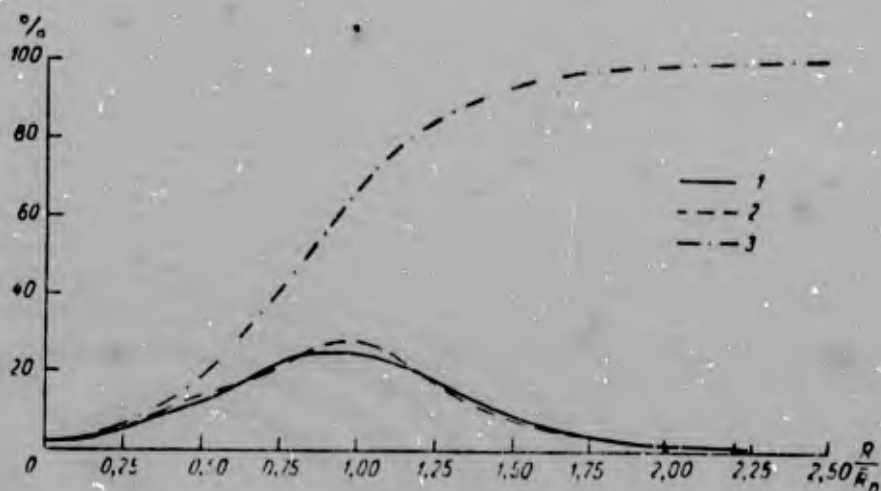


Figure 8. Graph of the distribution of relative precipitation values for the WER for cases of moderate and heavy precipitation (for  $R_t \geq 2$  mm).

1. curve of the frequency of relative values of  $R/\bar{R}_{\text{area}}$ , average of 51 cases for the test and control areas;
2. the same, but for eight cases for the test area and artificial modification;
3. distribution function for the cases in curve 1.

distribution function, one may determine a number of other characteristics of the horizontal field of precipitation. For example, the mode and median are close to each other and are less than the arithmetic mean (0.85 and 0.93, respectively). Extreme relative values  $R/\bar{R}_{\text{area}}$  are possible 0.0 to 2.25 from their arithmetic mean, but one may determine the probability of any gradation or sum of gradations of  $R/\bar{R}_{\text{area}}$  from the graph. For example, the probability of  $0.75 < R/\bar{R}_{\text{area}} < 1.25$  is 66%, for  $0.5 < R/\bar{R}_{\text{area}} < 1.5$  it is 86%, and for  $0.0 < R/\bar{R}_{\text{area}} < 2.0$  it is 99%.

The disadvantage of this type of distribution function is that one must know the arithmetic mean of the precipitation for the area (or for

the region in which the precipitation falls in general), but this may be obtained easily with punch-card computers. The positive aspect of this method is its independence of the precipitation intensity.

#### 5. Reasons for Horizontal Inhomogeneity of Steady Precipitation

The data in the meteorological literature [1-4, 7, 8, 10, 11, 13-15], the analysis of the rain-gage data from the WER, and flights in zones of steady precipitation and in the clouds from which it falls indicate that the following are the causes of the patchiness of the precipitation that appears on the charts: 1) inhomogeneities of the cloud structure, 2) topography, 3) large industrial centers, 4) forests and other inhomogeneities of the earth's surface, 5) differences in the position of the instruments, 6) random errors in the observational data.

During the cold half of the year, the precipitation in the WER was measured by one type of instrument (the Tret'iakov rain gage). Most of the random errors in analyzing the precipitation charts were eliminated by the high density of the rain-gage network and by critical examination of the tables of observational data. Systematic errors caused by instrument characteristics and the instrument mounting should not exceed 10%, as we know from [3], and cannot be the cause of the patchiness, in which the precipitation values vary by several factors.

There are no large forests in the WER, but in any event precipitation changes due to forests [7] and other surface features are of the same order as or are even smaller than the variations due to the position of the rain gages, so this factor cannot play any substantial role in the formation of patches.

Both sections of the WER comprise a uniform plain with prevailing elevations of about 100 m, intersected by shallow, gently sloping valleys of rivers and creeks and by gullies. The principal rivers in the

control area are the Gnily Yelanets, Gromokley, and Ingul; those in the test area are the Ingulets, Saksagan', and Bazavluk. At the bottoms of some river valleys the elevation drops to 40 to 20 m.

Composite charts of the precipitation patches were composed by groups of precipitation periods with similar wind directions. A comparison of these composite charts, as well as charts for individual cases of precipitation, with the topography of the WER (a hypsometric chart) did not disclose any localization of either positive or negative patches.

The role of small topographic irregularities may best be determined by analyzing the data with respect to the synoptic conditions and the wind, and by grouping the pluviometric stations by type of topography and relative or absolute elevation of the stations. Although this has not yet been done, it may be assumed that the topographic features will play a secondary role in the formation of precipitation patchiness.

It is a well known fact that frontal Ns-As clouds have inhomogeneous structure. Frequently, what is determined as Ns-As is sometimes an obvious and sometimes a masked conglomeration of multilayered Sc and Ac together with Cb, Cu con, and Ac cas. In winter atmospheric fronts, as in the formation of convective clouds in homogeneous air masses, there are cells of most active cloud and precipitation formation. Of course, these develop against the background of a general lifting of the air mass and continuous or nearly continuous cloud cover. The extent of this analogy differs in various processes, but is always present. Published investigations [2, 4, 14, et al.] and observational data dealing with this question are limited, hence further special vertical and horizontal soundings of fronts must be made. The data of such soundings could be compared with the data of a dense pluviometric or precipitation-gage network.

The effect of the factories of Krivoy Rog on the formation of clouds above them can be traced only for stratocumulus clouds. This effect is especially clear when the cloud cover is continuous, in which case domes or ridges protrude above the Sc top over the factories. The parameters

of such domes were measured specially on 10 and 11 November 1961. We will not give data on the inhomogeneity of the cloud cover for Krivoy Rog and elsewhere at this time.

### Conclusions

1. In the cold half of the year, the passage of one or several atmospheric fronts in cyclones and troughs, accompanied by relatively steady precipitation, causes considerable inhomogeneity of the horizontal distribution of the precipitation. The observational data of the dense rain-gage network reveal elliptical zones of relatively higher (positive) and lower (negative) precipitation amounts. The average size of such zones (patches) together with the neighboring field of intermediate isohyets, is less than 100 to 200 km<sup>2</sup>.

2. The principal reason for the patchy nature of steady precipitation appears to be the inhomogeneous structure of the frontal and air-mass clouds: precipitation from Cb, Cu con, Ac cas interspersed with Ns-As or similar consolidations is responsible for the formation of positive patches with intermediate negative patches. This finding requires further confirmation, but support is already lent it through the available data by analysis of the inhomogeneity of the cloud structure and by the preponderance and higher intensity of the positive patches of precipitation.

3. The patchiness of steady winter precipitation on the level terrain of the WER is due not only to the inhomogeneous structure of the precipitating clouds but, to some extent, to the presence of large industrial complexes.

4. The character of the precipitation field indicates the need for obtaining average precipitation values. This averaging is desirable for areas considerably larger than the areas of the natural precipitation patches. The optimum areas for averaging the steady winter precipitation are 100 to 200 km<sup>2</sup>. The pluviometric gradients determined along

and across the drift of the cloud system are convenient characteristics of the averaged field of steady precipitation.

5. The variation of precipitation in individual showers is considerable. The variation within the test area and the control area of the WER is of the same order as the average value for the entire WER. On the other hand, the coefficients of correlation between  $\bar{R}_t$  and the corresponding precipitation at individual pluviometric stations were large. These circumstances, together with the law of random distribution of precipitation by stations indicates that the variation should be smaller on precipitation charts for longer periods (month, season, cold half of the year). However, this assumption is based on limited data and must be investigated further.

6. The large variation of precipitation in steady showers during the cold half of the year complicates evaluation of the results of cloud-seeding experiments. The possible increase due to artificial modification can be estimated from the averaged precipitation values and the pluviometric gradients even for small increases, but the results are approximate. The reliability will increase with increasing experimental data.

7. The development of a punch card file for the pluviometric stations will allow us to mechanize the analysis of observations and to simplify the solution of a number of problems. In particular, it is desirable to establish the extent to which the patchiness is smoothed when the intervals covered by the precipitation charts are increased, to use the direct observations of the stations instead of drawing and analyzing isohyet charts, to use longer observation series, etc. In this investigation, we have concentrated on revealing the characteristics of the entity studied and on describing it, and have been concerned only in part with explaining it, for which further analysis is required. The examined characteristics of the patchiness of steady precipitation should help reveal the details of the formation of precipitation in frontal clouds.

The small interval between isohyets assumed in the present investigation (0.5 mm) affords the opportunity for detecting small variations of precipitation. This approach was dictated by the need for developing a method of analysis that could be used to evaluate all artificial modification experiments, including those which result in only a small increase of precipitation. The small interval between isohyets and the small number of ineliminable errors serve to illustrate the concept of horizontal inhomogeneity of steady precipitation, but its basic features are demonstrated correctly by our data and method of analysis.

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