

JANUARY 1968
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**The Stored Water of Stratus and
Stratocumulus Clouds Over the Ukraine
in the Cold Half of the Year**

I.P. POLOVINA

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THE STORED WATER OF STRATUS AND STRATOCUMULUS CLOUDS
OVER THE UKRAINE IN THE COLD HALF OF THE YEAR

Translation of

Vodozapasy sloistykh i sloisto-kuchevykh oblakov v kholodnoe
polugodie nad Ukrainoi

by

I. P. Polovina

Kiev. Ukrainskii Nauchno-Issledovatel'skii Hidrometeorologicheskii
Institut, Trudy, No. 47: 69-78, 1965.

This translation was produced by the
American Meteorological Society under
Contract AF 19(628)-3880, through
the support and sponsorship of the

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
L. G. HANSCOM FIELD
BEDFORD, MASSACHUSETTS
01731

1. "The stored water of stratus and stratocumulus clouds over the Ukraine in the cold half of the year"
2. Polovina, I. P. "Vodozapasy sloistykh i sloisto-kuchevykh oblakov v kholodnoe polugodie nad Ukrainoi," Kiev. Ukrainskii Nauchno-Issledovatel'skii Gidrometeorologicheskii Institut, Trudy, No. 47: 69-78, 1965 [in Russian].
3. 14 typewritten pages
4. Date of translation: April 1966
5. Translator: George E. Brady, Jr.
6. Translated for Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, L. G. Hanscom Field, Bedford, Massachusetts, by the American Meteorological Society, Contract number AF 19(628)-3880.
7. Unclassified and complete

THE STORED WATER OF STRATUS AND STRATOCUMULUS CLOUDS OVER THE UKRAINE IN THE COLD HALF OF THE YEAR

by

I. P. Polovina

The stored water of St-Sc cloud masses is calculated on the basis of their lifetime, thickness, rate of transport, and average water content. The amount of precipitation that can be expected from these clouds is calculated on the assumption that the stored water will be completely precipitated.

Data on the stored water of a cloud system are an important factor in determining whether it is feasible to modify these clouds to initiate precipitation. The amount of precipitation that can be produced by modifying the clouds can be calculated from these data. The possibility of modifying clouds to produce precipitation that will reach the ground depends on the basic characteristics of the clouds, viz., temperature, thickness, water content, and height of the cloud base above the ground. St and Sc are the principal objects of modification over the Ukraine in the cold half of the year (November-March). It has been shown in publications of the Ukrainian Hydrometeorological Research Institute (M. F. Leonov, G. I. Perelet, G. F. Prihot'ko) that although the stored water content may be very small at a given moment, the moisture carried by these clouds can be precipitated and the amount of precipitation can be increased considerably over limited areas by appropriate choice of seeding strips, keeping in mind that St-Sc move at relatively high speeds.

The aforementioned St-Sc parameters were determined from the data of hourly observations of clouds and other atmospheric phenomena made at the air weather stations in Khar'kov, Kiev, Odessa, and L'vov, from the results of aircraft and rawin soundings of the atmosphere at these points, and from the synoptic records of the Kiev Weather Bureau from 1955 through 1960.

Preliminary analysis showed that errors had been made in determining cloud types by ground observations, especially at night. Therefore, the hourly observations could not be used directly to determine the lifetime of St and Sc clouds. To eliminate errors in the determination of cloud types, the data of cloud observations were analyzed carefully with recourse to the data of aircraft soundings, observations of cloud heights and precipitation, and synoptic charts.

First, the St-Sc lifetimes for November-March were determined for each point (Khar'kov, Kiev, Odessa, and L'vov). Only those cases were considered where continuous cloud cover persisted for six hours or more, since the moisture storage in clouds is usually negligible for lifetimes shorter than six hours (table 1). Table 1 shows that in most cases the lifetime did not exceed 12 hours. On the average for the cold half of the year, the frequency of clouds with a lifetime of 6 to 12 hours is about 45%, with the exception of L'vov, where it reaches 54%. Clouds of this duration occur most frequently in February and March, less often in November. The absolute maximum lifetimes, in excess of 100 hours, occur in November and December. In December 1957, St-Sc existed over Khar'kov continuously for 297 hours. Although the frequency of St-Sc with a lifetime of 6 to 12 hours is about 50%, their contribution to the total duration is approximately 15-20%. Table 1 indicates that from the standpoint of duration, St-Sc are favorable for modification. Aircraft soundings, from which thickness, temperature, and height of the base above the ground could be determined, were matched to each cloud period. It should be noted that in the time span we examined, quite often soundings were made at 6 hour intervals rather than the normal twice-daily soundings.

When extended periods with St-Sc are analysed, the problem of the representativeness of the individual ascents, i. e. , the problem of whether a temperature sounding is typical for a corresponding time interval, proved to be ambiguous. It is quite apparent that the representativeness of each specific case is determined by the general nature of the

Table 1

Frequency (%) of Different St-Sc Lifetimes in the Cold Half of the Year over the Ukraine

Month	Lifetime, hours						Max. obs. lifetime of periods, hr.	Number of cases (periods)
	6-12	13-24	25-36	37-48	49-60	>60		
L'vov								
January . . .	44,7	27,7	3,5	8,5	4,3	6,3	101	47
February . . .	68,1	15,0	8,5	2,0	6,4	—	58	47
March . . .	50,0	33,4	7,1	7,1	2,4	—	53	42
November . . .	45,6	27,3	7,6	6,0	4,5	9,0	110	66
December . . .	64,7	27,3	2,0	2,0	—	4,0	76	51
Half year . . .	54,1	26,1	6,7	5,1	3,6	4,4		253
Odessa								
January . . .	44,4	19,7	18,0	8,2	4,9	4,8	113	61
February . . .	37,0	28,1	15,2	8,7	4,4	6,6	101	46
March . . .	48,9	33,4	2,2	6,7	6,7	2,2	77	45
November . . .	49,2	25,5	10,0	5,1	1,7	8,5	186	59
December . . .	36,8	24,5	14,3	4,1	8,1	12,2	134	49
Half year . . .	43,5	25,8	12,3	6,5	5,0	6,9		260
Kiev								
January . . .	39,5	25,4	14,3	8,0	3,2	9,6	146	63
February . . .	54,0	25,8	9,3	3,7	1,8	5,4	100	54
March . . .	52,8	23,5	12,8	—	3,6	7,3	77	55
November . . .	35,1	32,4	10,9	2,8	8,1	10,7	128	74
December . . .	45,3	20,3	9,4	4,6	6,3	14,1	153	64
Half year . . .	44,5	25,8	11,3	3,9	4,8	9,7		310
Khar'kov								
January . . .	40,0	33,8	13,8	6,2	5,0	1,2	75	80
February . . .	45,0	25,0	15,0	5,0	3,3	6,7	79	60
March . . .	62,5	21,8	9,4	6,3	—	—	44	64
November . . .	37,2	28,8	10,2	6,8	3,4	13,6	113	59
December . . .	41,7	16,6	16,6	6,7	8,3	10,1	297	60
Half year . . .	45,2	25,7	13,0	6,2	4,0	5,9		323

development of meteorological processes, but even under specific conditions, the degree of change of the individual cloud characteristics differs. The base of the cloud experiences especially strong fluctuations [3]. Therefore, when there were adequate sounding data for the individual periods, the representativeness of each ascent was determined

primarily by the fluctuation of the base, which results in a change in the cloud thickness. The height of the cloud base was taken from the results of hourly pibal observations. On the average, one ascent was enough to determine the cloud characteristics for a period of 8 to 10 hrs, when the aerological data were available. Data on the height of the base, the thickness, and the temperature were taken from the aircraft sounding data in 75% of the cases and from radiosonde observations in 25% of the cases. We know that St-Sc are mainly found below inversion layers [1, 2, 4]. This circumstance was used to determine the cloud tops from radiosonde data. Since direct measurements of liquid-water content were not available in most cases, the stored water was calculated from the mean liquid-water content values of St-Sc as a function of the thickness and temperature as given in [5]. On the basis of temperature, the clouds were classified as supercooled (if the temperature at the top was $\leq -4.0^\circ$) and warm (if the temperature at the top was $> -4.0^\circ$). This division was made because dry ice is quite an effective seeding agent for initiating artificial precipitation when the temperature is $\leq -4.0^\circ$.

The relation of the cloud thickness to the height of the base is the major factor that determines whether the precipitation will reach the ground. The cloud thickness determines the potential storage of moisture that can participate in the formation of precipitation and the size of the artificially induced precipitation elements, while the height of the base determines the probability that the precipitation will evaporate in the air below the cloud. This relationship, which can be called the criterion of suitability of St-Sc for the initiation of artificial precipitation, has not yet been established. It can be taken as an approximation that artificially produced precipitation will reach the ground if the cloud is more than 300 m thick and its base is not more than 1000 m above the earth's surface.

Allowing for the roughness of the criterion and the fact that the results presented may prove useful for other purposes, all further calculations will be made separately 1) for all clouds, selected as mentioned

above, 2) for the same clouds, but with the temperature $\leq -4.0^{\circ}$ (supercooled), and 3) for supercooled clouds which conform to the requirements of the criterion.

In table 2 the average and, in parentheses, the maximum and minimum duration of St-Sc at each of the stations examined is given for each month of the cold half of the year. The contribution of individual cloud characteristics to the reduction of the number of hours with clouds suitable for modification can be determined by comparing the data of columns 2-4. Table 2 shows that the temperature and criterion limitations successively reduce the number of hours with clouds suitable for modification. At all stations, the maximum number of

Table 2
Lifetime (in hours) of St-Sc with Various Characteristics

Station	Cloud characteristics		
	All clouds	with min. temp. 4°C	Meeting criterion
1	2	3	4
January			
L'vov	169 (255-124)	133 (177-76)	82 (101-61)
Odessa	242 (311-95)	141 (230-35)	58 (92-0)
Kiev	274 (437-181)	186 (370-108)	103 (132-71)
Khar'kov	280 (322-208)	165 (251-130)	106 (129-79)
February			
L'vov	117 (258-57)	90 (227-27)	40 (96-19)
Odessa	188 (278-103)	72 (174-32)	42 (103-20)
Kiev	150 (225-39)	74 (180-31)	50 (115-14)
Khar'kov	214 (315-14)	136 (233-14)	72 (116-0)
March			
L'vov	115 (174-27)	68 (116-16)	29 (54-0)
Odessa	132 (215-14)	68 (130-28)	43 (102-14)
Kiev	175 (277-60)	93 (154-47)	49 (108-14)
Khar'kov	141 (220-52)	93 (173-34)	43 (63-21)
November			
L'vov	257 (386-197)	67 (161-23)	40 (112-12)
Odessa	250 (302-193)	53 (112-8)	22 (59-0)
Kiev	329 (412-243)	124 (215-72)	58 (96-18)
Khar'kov	268 (446-181)	91 (126-56)	54 (68-36)
December			
L'vov	124 (188-51)	62 (110-13)	20 (44-9)
Odessa	247 (335-192)	64 (114-0)	23 (44-0)
Kiev	307 (359-201)	133 (216-97)	69 (101-51)
Khar'kov	336 (496-148)	122 (348-51)	81 (235-13)

hours with St-Sc occurred, on the average, in November-December and the minimum occurred in February-March. February and March show particularly sharp annual fluctuations in the number of hours with clouds. For example, in Khar'kov, there were clouds for only 14 hours in February 1956, although the average number of hours with clouds during the six year period was 214. At all stations, January had the greatest number of hours with clouds that met the criterion, viz., 60 hours in the southwestern regions of the Ukraine, 80 hours in the western regions, and more than 100 hours in the northern and eastern regions. The lifetime of these clouds during November-December is about 20 hours in the southwestern regions, 20 to 40 hours in the western regions, and 50 to 80 hours in the northern and eastern regions. The lifetime in these regions during February and March is 40, 30 to 40, and 50 to 70 hours, respectively. The data of table 2 show large annual fluctuations of the number of hours with suitable clouds as well as the possibility that such opportunities for modification will not exist at all. This latter situation is most probable in the southwestern regions of the Ukraine.

For other kinds of calculation, in particular, for planning modification operations, it is of interest to have data on the frequency of durations of clouds suitable for the initiation of precipitation (table 3).

Table 3 shows that over all stations the duration of clouds that meet the criterion and have a temperature $\leq -4.0^{\circ}$ does not exceed 12 hours in most cases. Roughly 12% of the clouds that meet the criterion last more than 24 hours, but, during the period under consideration, somewhat more than 30% of the total number of hours have clouds suitable for the initiation of precipitation. The maximum duration of these clouds is 60 hours in Odessa and 87 hours in Khar'kov.

In addition to the characteristics examined, data on the transport velocity of clouds is needed for calculating the storage of water. These data were obtained from observations of pilot balloons with a radar reflector; 2610 ascents were used in all. In addition, the average velocity for the entire layer of clouds was determined. Data on the rate of transport of different groups of St-Sc in the cold half of the year over the Ukraine are given in table 4.

Table 3
Frequency (%) of Different Lifetimes of St-Sc
Suitable for Modification

Cloud Characteristic	Duration, Hours						Max. Dura- tion, Hours	No. of Cases (Periods)
	6-12	13-21	25-36	37-48	49-60	>60		
L'vov								
Supercooled . . .	55,0	30,0	7,0	3,5	2,1	2,1	78	142
Meet Criterion :	61,0	25,3	6,9	3,4	3,4	—	60	87
Odessa								
Supercooled . . .	45,4	32,7	11,8	5,9	2,5	1,7	71	119
Meet Criterion :	63,3	24,0	10,1	1,3	—	1,3	71	79
Kiev								
Supercooled . . .	55,0	24,8	8,6	5,1	2,5	4,0	96	198
Meet Criterion :	62,0	26,0	7,8	1,4	1,4	1,4	80	142
Khar'kov								
Supercooled . . .	50,8	28,7	11,3	4,6	2,0	2,6	98	195
Meet Criterion :	59,8	28,8	8,1	2,0	—	1,3	87	149

In analyzing table 4, one first notes that the frequency of the rates of transport is remarkably similar for all gradations taken for all groups

Table 4
Frequency (%) of Rates of Transport of St-Sc in the Cold
Half of the Year over the Ukraine

Velocity range, m/sec											Av. vel., m/sec	No. of cases
1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22		
All clouds												
4,4	14,1	24,0	19,8	14,4	9,7	5,6	4,6	2,1	1,0	0,3	8,0	2610
Supercooled clouds												
3,9	13,3	23,8	21,4	15,8	9,7	5,7	3,6	1,6	0,9	0,3	7,9	1259
Clouds that meet criterion												
3,3	12,7	22,1	21,6	15,7	10,7	6,8	4,1	1,7	0,9	0,2	8,1	661

of clouds. For St-Sc, the rate of transport ranges from 1 to 22 m/sec (from 3 or 4 to 80 km/hr), the average is 8 m/sec, while 5 to 8 m/sec is most often observed (44%), and in 40% of the cases it exceeded 8 m/sec.

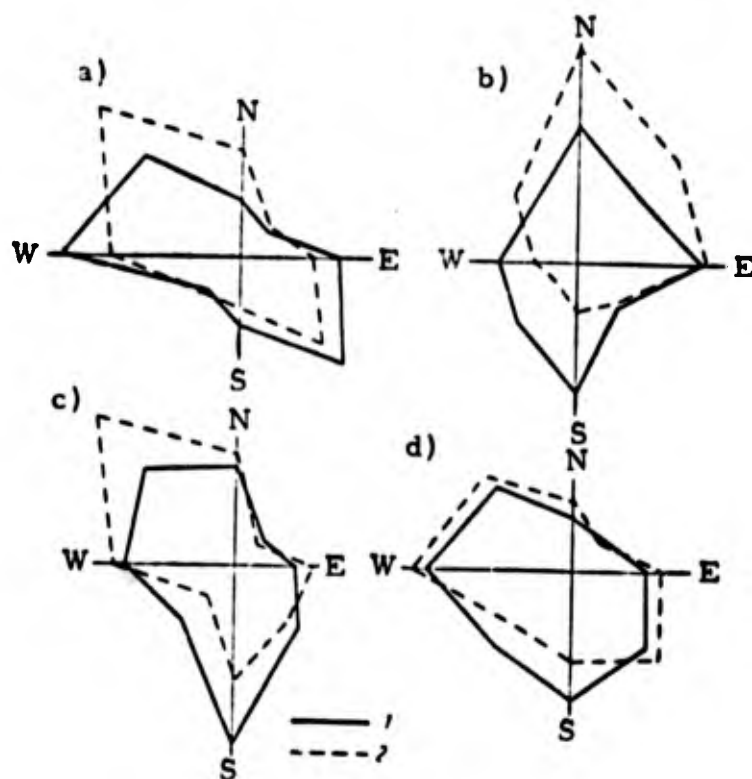


Figure 1. Frequency of wind directions in St-Sc cloud layers in the cold half of the year.

a) L'vov; b) Odessa; c) Kiev; d) Khar'kov. 1. All clouds; 2. Clouds meeting criterion.

In connection with the problem under consideration, data on the direction of cloud transport are of great value for subsequent calculations. Figure 1 shows the frequency of the direction of transport of all clouds and of clouds that meet the criterion, for all stations. Over L'vov, St-Sc move mainly from the west and northwest (23.6 and 18.1% of the cases, respectively) and from the southeast (19.2%). For the clouds that meet the criterion, the frequency of movement from the northwest increases to 26.4%, and from the west and southwest it

decreases to 16.8 and 15.2%, respectively. Over Odessa, in general, the direction of movement of all clouds has about the same probability (17.4, 16.2, and 16.8% from the north, east, and south, respectively), while the probabilities for clouds that meet the criterion are 27.2, 21.8, and 16.4%, respectively from the north, northeast, and east. Over Kiev, the clouds most often move from the south (22.5%) and northwest (17.2%), while those clouds that are suitable for modification move most often from the northwest (26.1%). The frequency of the direction of movement of clouds over Khar'kov is almost the same for all directions (14 to 19%), except from the north, northeast, and east. Clouds suitable for modification move mainly from the west (20.7%), northwest (16.7%), and southeast (16.1%). Thus, clouds that are suitable for modification move from the west and northwest or from the southeast, i. e., from two nearly opposite directions, over a large part of the Ukraine, excepting the southwestern regions.

The data on the storage of water in clouds at any given time, their duration, and the rates of transport were used to calculate the amount of moisture contained in each of the clouds massifs by the following relationship:

$$Q = 3,6 \cdot 10^{-3} P v \tau, \quad (1)$$

where Q is the total amount of liquid-droplet moisture that is transported across one meter of surface perpendicular to the flow (tons); P is the water storage at any given time in a cloud layer (g/m^2); v is the rate of transport of the clouds (m/sec); and τ is the lifetime of the clouds over a station (hours).

Table 5 gives the results of calculation of the stored water of all the clouds and of those clouds that meet the criterion. On the average, the greatest amount of moisture is transported in November-December (Kiev and Khar'kov) and in November-January (L'vov and Odessa). The greatest amount of moisture is stored in warm clouds during this period, and in Odessa during the remaining months as well. The maximum amount

of moisture in clouds that are suitable for modification is transported over all stations in January.

The possible precipitation content was calculated by the relationship

$$R = \frac{Pv \cos \alpha \cdot 10^{-3}}{l}, \quad (2)$$

where α is an angle less than 45° to the prevailing direction of cloud movement and l is the length (km) of the zone containing the stored water.

Formulas (1) and (2) were proposed by M. P. Leonov, G. I. Perelet, and G. F. Prikhot'ko.

In converting water storage into precipitation, it was arbitrarily assumed that all the moisture reached the ground and was evenly distributed over a 50 km strip in the prevailing direction of cloud movement.

Table 6 gives, for each station, the average, maximum, and minimum (in parentheses) precipitation yield on the assumption that all the stored water transported by the St-Sc was precipitated. The amount of precipitation thus calculated is given for all clouds and for clouds that meet the criterion.

For comparison, these precipitation amounts are expressed in percentages of the corresponding long-range average [see table 6]. Table 6 shows that, at all stations, the maximum amount of precipitation that can be obtained when all St-Sc are precipitated occurs in November (8 to 16 mm), the minimum in March (4 to 5 mm). The total amount of precipitation for the entire half year is 25 mm in the western regions and 55 mm in the northern regions of the Ukraine, which is 16 to 26% of the norm.

Of greatest interest are the data on the possible amount of precipitation from clouds which meet the criterion, i. e., that precipitation which can be obtained at present by dry-ice modification of St-Sc. In limited areas, on the average, from 1.4 mm in November-December

Table 5

Amount of Liquid-Droplet Moisture Transported by St-Sc in the Cold Half of the Year over the Ukraine (tons/m²)

Month	Average		Maximum		Minimum	
	All clouds	Meeting Criterion	All clouds	Meeting Criterion	All clouds	Meeting Criterion
L'vov						
January	415	171	1225	381	101	82
February	224	160	437	424	35	21
March	200	105	313	229	88	12
November	419	120	587	221	277	44
December	222	104	376	258	52	97
Odessa						
January	570	270	891	466	120	46
February	373	107	671	311	91	46
March	340	148	755	336	78	50
November	493	44	780	135	247	0
December	485	130	700	248	386	69
Kiev						
January	739	395	1111	681	427	317
February	562	286	868	527	254	47
March	379	219	637	396	127	87
November	1072	301	1624	570	749	140
December	875	332	1462	521	544	266
Khar'kov						
January	774	110	973	542	525	237
February	499	321	1145	593	10	10
March	333	171	705	265	53	45
November	841	307	1267	626	498	113
December	825	308	1082	733	360	51

to 6.1 mm of precipitation in January or from 4 to 22% of the long-range average [norm] can be obtained in the western regions of the Ukraine from the precipitation of the stored water of St-Sc. From 0.8 to 3.1 mm, respectively, are obtained in southern regions, which is 3 to 13% of the norm. In the northern and eastern regions of the Ukraine, the amount of precipitation from St-Sc in March, on the average, is 2 to 3 mm and in January about 6 mm, or 7 to 18% of the norm. The average amount of precipitation for the cold half of the year is 8 mm in the southern regions, 14 mm in the western, and about 20 mm in the northern and eastern

Table 6

Amount of Precipitation (mm) from St-Sc Given Total Precipitation of the Stored Water in a 50-km Zone

Station	All clouds	Clouds that meet criterion	% of Norm	
			All clouds	Clouds that meet criterion
January				
L'vov	7.1 (20.4-2.1)	6.1 (19.2-1.5)	25	22
Odessa	7.8 (13.9-1.5)	3.1 (5.0-0.0)	37	13
Kiev	11.1 (17.1-6.9)	5.7 (10.3-3.4)	29	15
Khar'kov	11.5 (13.7-8.3)	6.0 (8.2-3.2)	34	18
February				
L'vov	3.6 (6.6-0.6)	2.9 (5.9-0.5)	13	10
Odessa	6.0 (10.3-1.5)	1.3 (2.9-0.3)	35	8
Kiev	8.4 (13.4-3.5)	3.2 (7.5-0.5)	23	9
Khar'kov	7.9 (18.4-0.1)	4.6 (10.2-0.0)	30	18
March				
L'vov	3.7 (6.7-1.5)	1.9 (4.0-0.0)	11	5
Odessa	5.3 (13.2-1.2)	2.1 (5.2-0.6)	26	10
Kiev	5.4 (8.8-1.4)	2.9 (5.8-0.8)	12	7
Khar'kov	4.9 (9.6-0.8)	2.4 (4.2-0.4)	15	8
November				
L'vov	7.6 (9.3-4.3)	1.6 (2.9-0.0)	16	4
Odessa	8.7 (12.1-1.4)	0.7 (1.7-0.0)	32	3
Kiev	16.3 (23.7-11.6)	4.1 (7.5-1.0)	35	9
Khar'kov	12.8 (20.0-7.3)	4.0 (6.5-1.7)	32	10
December				
L'vov	3.5 (6.0-0.8)	1.4 (3.0-0.3)	11	4
Odessa	7.2 (9.8-5.9)	0.8 (1.5-0.0)	27	3
Kiev	13.4 (22.3-8.1)	3.7 (6.0-2.1)	32	9
Khar'kov	10.5 (16.7-4.4)	4.7 (11.1-1.0)	28	12
Half Year				
L'vov	21.6	13.9	16	8
Odessa	36.0	8.0	31	7
Kiev	54.7	19.6	26	9
Khar'kov	47.6	21.7	28	13

regions of the Ukraine, or 7 to 13% of the norm. In some years sharp deviations from the possible average amount of induced precipitation are observed. In almost all months of the season, with the exception of January, for the northern and eastern regions of the Ukraine, cases are probable where the conditions for artificial initiation of precipitation are completely absent and the possible precipitation yield is 1 to 2% of the norm.

On the basis of the investigation of the water storage and other characteristics of St-Sc in the cold half of the year over the Ukraine, and the calculation by these data of the potential amounts of artificially induced precipitation, the following conclusions can be drawn.

1. During the period from November to March, the basic characteristics of St-Sc over the Ukraine make them suitable for dry-ice modification. On the average, the maximum number of hours (250 to 300) with St-Sc is in November-December at all stations, but for clouds that are suitable for modification the maximum number of hours is in January (60 hours in the southwestern and northern regions and 100 hours in the northeastern regions of the Ukraine).
2. The greatest amount of moisture in the northern and eastern regions comes in November-December, in the southwestern and western regions, in November-January. The largest amounts of stored water are contained in warm clouds at this time, and in the southwestern regions, during the remaining months as well.
3. When the stored water of St-Sc is fully precipitated, the potential amount of precipitation varies from 1.4 to 6.1 mm for individual months in the western regions, 0.7 to 3.1 mm in the southern regions, and 2.4 to 6.0 mm in the northern and eastern regions. The average amount of precipitation in the cold half of the year is 8 mm in the southern regions, 14 mm in the western regions, and about 20 mm in the northern and eastern regions of the Ukraine, or 7 to 13% of the norm.

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