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Cloud modification for rain enhancement

(Longtime research carried out in Moldova and Ukraine)

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Abstract

The paper summarizes the results of the longtime cloud modification experimental research in Moldova and Ukraine aimed at rain enhancement. The research enabled to develop a unique technology of cloud seeding that provided significant rain augmentation from clouds of different types. The basic principle of the technology lies in selecting seeding target sites within cloud systems based on data related to its structure, evolution stage, and microphysical parameters at the time of supposed seeding. It was shown that the efficiency increases considerably if the seeding is performed precisely into the layer whose microphysical characteristics are appropriate for the transformations needed for rain production, namely, crystallization of droplet water and an abrupt increase in crystal concentration by 1-2 orders of magnitude. It was also shown that violation of this principle reduces seeding efficiency to the levels that make it economically senseless.

Keywords: rainfall, precipitation, clouds, cloud modification.

1 Introduction

In the early 60s, scientifically sound rain-enhancement types of experiments were performed in many countries. In the U.S.A., these studies reached an especially large scale [1–8], sometimes achieving augmentation as high as 12-20%. During 12 years of field experiments, the total of 665 mm of rain augmentation was achieved in Santa-Clara Valley (California), which is 12.7% increase to the expected amount. Even higher rain enhancement was obtained in Mexico, over the Necaxa river basin that sometimes exceeded 50%.

In Japan, cloud modification resulted in more than 20% rain augmentation rain, in some cases reaching dramatic 150%, while enhanced rain was registered at 50-100 km distance from the cloud-seeding area [9]. Long-term studies in cloud modification have been carried out in Australia, China, France, Italy, Spain, and other countries.

Cloud modification technology of static seeding, developed in Israel, enabled to increase rainfall over the northern part of the country by 17-18%, as was shown in long-term experiments. However, the approach proved inefficient over the southern regions [10–12].

Observations performed in the present study with the help of MRL-5 radar suggest that there is a significant potential for rain enhancement over central and southern Israel due to specific properties of clouds usually observed over these areas.

During the raining season (December-March), the upper bound of Cu cong and Cb is mostly at the height of 5-7 km (80% of observed cases). The temperatures at these heights range within minus 10^{o}C-minus 20^{o}C. The world-wide rain enhancement experience accumulated over different regions (Cuba, Ukraine, Moldova, Volga region, Middle Asia, Syria) shows that those conditions are optimal for achieving maximum rain augmentation [13–18]. Using an appropriate technique, seeding with glaciogens and refrigerants at the stage of cloud formation demonstrated high efficiency.

Moreover, the main formation stage of Cb, Ns, Sc and St usually occurs over the vast and warm Mediterranean basin and has a high liquid water and total water content.

The question then arises why, in view of this high potential, did cloud modification over southern Israel yield zero effect?

In our opinion, the reason is that the rain enhancement technology developed in Israel, is based on seeding an atmospheric layer expected to be shortly involved in rain production by the accumulating clouds. This seeding strategy in often unable to ensure the impact of the reagents on the totality variety of microphysical and dynamic processes taking place in clouds of different types at various stages of their development. This conclusion is based on longtime and large scale studies carried out in the former USSR, among them the exploratory and field experiments personally conducted by the authors of this paper in Moldova and Ukraine.

In the USSR, the works in rain enhancement commenced in the late1940s at the Head Geophysical Observatory (HGO) in Leningrad and the Central Aerological Observatory (CAO) in Moscow, later joined by the Institute for Experimental Meteorology (IEM) branches in the Middle Asia, Ukraine, and Caucasus, by Moldavian Paramilitary Service for hydrometeorological modification, as well as by other academic and production bodies.

In the 1980s-90s, CAO successfully carried out several large-scale rain enhancement projects, including a number of joint international ones. The projects were based on a wide variety of technologies and technical equipment that had been developed by this time.

Table 1 and 2 shows some results of research and field experiments carried out in the former USSR [13–15, 19–25].

In all the experiments presented, steady positive results were observed.

The Moldova experimental site with its unique team of experts and technological capacities enabled to carry out, in cooperation with CAO and the IEM Ukrainian branch, longtime exploratory and field experiments in rain enhancement by seeding winter, summer, and midseason clouds. Since rain production processes in Moldova and Ukraine are climatologically similar, the paper presents a combined description of the work carried out in the two republics.

In the years following the experiments in Moldova and Ukraine presented in this paper, the authors and their followers carried out further studies, among them:

- a two-year experiment in seeding convective cloud systems not producing natural rainfall [21];
- experiments in rain enhancement from midseason clouds over some Ukrainian areas [22];
- the analysis of numerous industrial experiments in seeding convective cloud systems in Argentine, Brazil and Bulgaria.

The results of these studies confirmed both the actuality and the correctness of the conclusions made in the present paper.

Country	Cloud type	Number of experimental units	Number of control units	Control technique	Efficiency (%)
Russia (the town of Penza)	Cu Cong, Cb $6 \leq Htop < 8$km	106	87	Randomization	100
Cuba (research carried out by Russian experts)	Cu Cong, Cb Clusters	53	39	Randomization	60
	Cu Cong, Cb Single	37	41	Randomization	87
Ukraine	Isolated	52	22	Randomization	86
Ukraine	Multicell	58	31	Randomization	55
Ukraine	St, Sc, As, Ns	156 day 1974-1980		Control site	63
Ukraine	Cu Cong, Cb Clusters	1981-1985		Randomization	40
	Cu Cong, Cb Single	1981-1985		Randomization	50
Moldova	St, Sc, As, Ns (Winter) Cu Cong, Cb (Summer)	1985-1990 125 day Fixed target Fixed target		Historical regression technique and control site	15-19 27
Uzbekistan	St, Sc, As, Ns (Winter)	1984-1987 35 day Fixed target		Historical regression technique	15
Georgia	Cu Cong, Cb, St, Sc, As, Ns (Summer)	Fixed target		Hydrological technique	20
Georgia	Cu Cong, Cb, St, Sc, As, Ns (Summer)	Fixed target		Historical regression technique	25

Table 1: Rainfall enhancement efficiency in Ukraine, Moldova, Russia, Georgia and Cuba.

Season	Actual amount	Evaluation of the amount of rainfall	The effect of seeding (km^3 of additional water)	The effect of seeding (in %)
Syria				
1991-92	33.86	29.07	4.79	16.5
1992-93	28.81	24.73	4.08	16.5
1993-94	30.25	27.08	3.17	11.7
1995*	14.06	13.15	0.91	6.9
1995-96	36.61	34.02	2.59	7.6
1996-97	30.63	26.92	3.71	13.8
1997-98	33.68	32.13	1.55	4.8
1998-99	24.01	21.90	2.11	9.7
1999-2000	25.00	21.77	3.23	14.8
Iran				
1999	8.34	6.48	1.86	28.7
2000	2.46	1.75	0.71	40.3
Portugal				
1999 8 working days (22-29 October)			0.37	7.4

Table 2: Results of rain enhancement performed by CAO in Syria, Iran, and Portugal.

2 Methods and results of rain enhancement from winter and midseason clouds over the Ukrainian steppe

Works in rain enhancement in Ukraine began in 1958 [26, 27] and were performed at the experimental meteorological testing site (EMS), equipped with precipitation network of 10.000 km^2 square (one station per 10-20 km^2). EMS contained a radar station composed of MRL-1, MPL-2 and “Bolshoy Ochag”, later replaced by MRL-5 radar. In addition, the station had a flying control radar for monitoring “Ekran-D” aircraft, a radio-drive, and an upper air sounding station.

Seeding was performed with the use of 4 IL-14 planes of 8-hour flight endurance, with cruising altitude up to 6 km and 220-350 km/h operational speed range. The planes were equipped with devices for measuring cruise speed, pressure, relative air humidity, and temperature, as well as with a photomicrographic setup, an electronic thermometer, a device for registering liquid-water content in clouds, crystal counter, and seeding devices. In 1980, AN-26, AN-30 and Yak-40 planes were put in operation as well.

As a cloud seeding reagent, artificial ice CO_2 was used (the cold reagent group). ADG-1 station crushed solid dry CO_2 blocks into 5-10 mm granules, providing the dosage of 50-3,000 gr/min. Solid CO_2 was transported in two heat-insulated containers of 1.5t total capacity.

Authorization of an operational flight was issued after the analysis of current weather pattern on the basis of radar data. On entering the prescribed area, a probe was performed. A seeding operation was authorized when a suitable area had been detected within the cloud system, that met certain criteria established as a result of the experiments [28–30]. It should be noted that criteria for Ns-As clouds yielding natural precipitation (Ns-As) differed from those related to air-mass clouds that do not produce natural rain (Sc, St, Ac).

Ns-As were considered to seeding-suitable if they contained droplet layers or mixed layers at least 500m thick and had the temperatures below minus 4^0C.

Air-mass Sc, St were considered to be seeding-suitable if they had droplet structure, the temperature below minus 4^0C and the lower boundary not exceeding 1000m. For Ac, the thickness was to be at least 600 m.

The seeding layout was calculated so that to ensure stretching the area of enhanced rain over the EMS [22, 31]. The seeding planes flew along straight parallel lines about 20 km long (the exact length depending on the wind speed) on the level of the upper boundary of the target layer. The distance between the lines varied within 3-4 km and was meant to be equal to the width of the crystallization zone [32].

CO_2 dosage varied within 100-700 g/km, being most often 400-500 g/km. The duration of seeding was set according to the availability of seeding-suitable cloud layers over the target area. In order to estimate the seeding effect, a technique was used based on determining the area covered with the enhanced rain on the ground, taking into account the correlations between changes in wind direction/speed with the height of the treated cloud layer, as well as the speed at which the band of the enhanced rain descended. The reliability of this technique was confirmed by radar observations [33]. The quantity of rain augmentation was determined as the difference between the mean precipitation layer over the target area following the modification and the analogous layer over the territory surrounding the target area. By

1972, the effects of 68 seeding experiments had been estimated, 56 of them involving Ns-As clouds and 12 involving Sc, St, Ac and As clouds that did not produce natural rain. Out of the 56 experiments, rain augmentation on the average of 0.04 mm was achieved in 54 trials, while two trials resulted in rain reduction of 0.11mm and of 0.04 mm. The mean rain augmentation over the 56 experiments was 0.74 mm, the maximum being 2.44 mm. The mean rain rate from Sc, St, Ac was close to 0.1 mm/h.

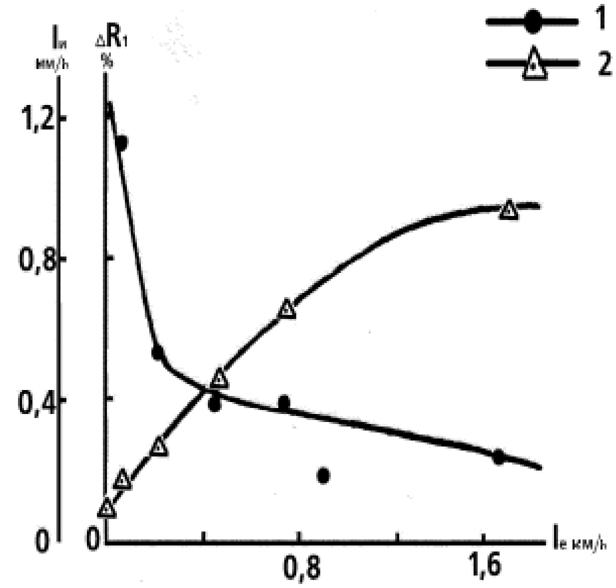

Figure 1: Dependence of relative augmentation (ΔR_1,%) and rate (I_a, mm/h) of enhanced rain on the natural rainfall rate (I_n, mm/h).

Fig. 1 shows the dependence of the the relative augmentation (ΔR_1,%) and intensity (I_a, mm/h) of enhanced rain on the natural rainfall rate (I_n, mm/h). The graphs in Fig. 1 show that augmentation of light precipitation exceeds 100%.

As the rate of natural rain increases, the values or relative augmentation of enhanced rain (ΔR_1) rapidly decrease. In contrast, the rate of enhanced rain (I_a) and, hence, its absolute quantity increases with the increase of I_n .

In the field conditions, it is very unlikely to achieve such augmentation values, since only in 42% of actual cases As-Ns layers that are seeding-suitable, can be found [29]. While analyzing the results of seeding experiments, we also took into consideration the length of the enhanced rain band in relation to the wind direction. Rain enhancement was observed within the band corresponding to the distance of 60-100 km, which is usually covered by a cloud carried over by wind during 2-3 hours. For Sc, St, and Ac the corresponding distance was calculated as 20-30 km, i.e. a 45 min-long carry-over.

In order to calculate the expected rain augmentation resulting from systematic seeding, it was taken into account that Ns-As cloud systems produce 35% of the total natural rain. The calculations suggested that in the case when all winter Ns-As, Sc, St and Ac are seeded, the expected augmentation would be 33-35% of the annual winter average.

Evolution of certain microphysical cloud parameters was one of the research issues. An increase by 1-2 orders of magnitude was observed in crystal concentration within the seeded areas of Ns-As, in 70% of cases the crystallization was absolute. The temperature increase within the seeded areas was found to be 0.2-0.6^{0}C, the maximum increase being 1.5^{0}C.

An important result was obtained from comparing the amount of rain augmentation with the current droplet water content within the seeded area. In naturally precipitating Ns-As, the amount of enhanced rain is by factor of 10 larger than the current droplet water content within the seeded area. In the case of Sc, St, and Ac, this ratio is below unity, usually within the range of 0.1-0.5. This finding suggests that Ns-As systems should be considered a proper seeding target, being the main source of enhanced rain.

Pilot experiments were carried out in January 1974 and January 1975 when clouds were seeded during the entire month, aimed at rain enhancement over a preset target area that was a circle of 20km diameter and 314 km^2 square.

The rain augmentation was measured as 63% in January 1974 and 41% in January 1975. Due to the wind impact, rain enhancement was observed over territories beyond the target area. Over the area of 3,600 km^2, which is by an order larger than the target square, a 20% augmentation was measured in 1974 and 18% in 1975. Totally, up to 9% augmentation was obtained from seeding Ns-As clouds, while only about 10% was the yield from Sc, St and Ac.

The main principle of the seeding technology developed in Ukraine was introducing the reagent precisely into the target cloud layer whose physical parameters can ensure microphysical transformations required for precipitation, namely, crystallization of droplet water and abrupt increase in crystal concentration by 1-2 orders of magnitude. When this principle was violated, the seeding efficiency proved too low to be economically reasonable [22].

3 Seeding summer convective clouds in Moldova

In Moldova, works in hydrometeorological modification started in 1964 and were aimed at preventing hail damage of crops. By 1972, a large technological complex was created over an area of 21,000 km^2, which enabled to investigate clouds of various types using both ground facilities and aircraft.

In order to estimate the impact of hail-protection cloud seeding on rainfall rate, most of target sites were covered with dense pluviograph network (one device per 8-10 km^2 over a total square of 700,000 hectares). This network enabled juxtaposing bar charts of rain rate and quantity with the corresponding radar data and seeding schemes. Seeding was performed with application of hail protection techniques by means of ground equipment, namely, specialized rockets containing AgI–based ice-producing reagents. A target area seeding within a cloud was chosen by a radar-based technique.

The scheme of this longtime experiment and the analysis of the results are presented in [15, 21].

In brief, it was found that cloud seeding of storm and hail-potential clouds, using hail-protection techniques, leads to a total rain augmentation of: 75% in case of moderate shower cloud; 55% in case of substantial shower cloud and 52% in the case of heavy shower cloud.

Seeding yielded 85% augmentation in feeble-rain clouds; 51% in light-rain clouds and 17% in giant-shower clouds. The data can be seen in the graphs in Fig. 2. The curves are calculated with a fair accuracy by the corresponding analytical expressions for seeded Q_s cells and non-seeded convective Q_c cells.

$$\begin{aligned} Q_s &= 0,164 Q_l^{-3,3} \exp(\frac{18,5}{Q_l}) \text{ (curve-row2)} \\ Q_c &= 0,498 Q_l^{-1,5} \exp(\frac{6}{Q_l}) \text{ (curve-row1).} \end{aligned}$$

The X-axis presents

- the spectrum of rain masses precipitating over the target area from naturally evolving convective cells.

The Y-axis presents

- curve 1: the recurrence distribution of mass spectrum of rain falling from naturally evolving convective cells;
- curve 2: the same as curve 1, for cells seeded using the hail-protection technique.

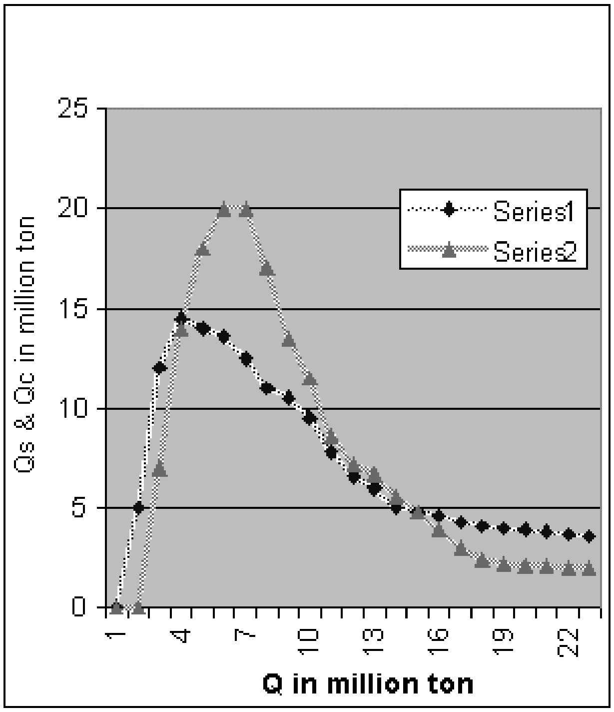

Figure 2: Rain enhancement obtained by seeding convective clouds using hail-protection techniques.

56 cloud systems were systematically seeded during 7 summer seasons over a part of the Moldova target territory of about 10,000 m^2, resulting in total rain augmentation of about 27% (the rain rate parameters and assessment techniques are presented in [34].

Dependences presented in Figs. 1 and 2 describe seeding results obtained in two independent experiments, over different target areas and clouds that differed in evolution processes. In the first experiment, the seeding was performed within winter stratus and stratocumulus, while in the second experiment the target were summer convective clouds.

The results suggest that seeding impact has the same trends regardless differences in cloud types. The sign and the scale of the effect depend on the stage of cloud evolution and the intensity of rain production within the cloud. The experiments show the need for careful selection of seeding targets in order to obtain the maximum rain enhancement; otherwise the result may be zero or even negative.

The above described experiments enable to define seeding conditions that appear to be universally optimal regardless regional characteristics. The conditions for seeding convective clouds with glaciogens or refrigerants in order to yield maximum rain enhancement are as follows.

- Seeding is to be performed at the stage of cloud cell formation prior to its dissipation. Seeding fully developed cells at the dissipation stage results in reduction of rain enhancement.

- Within the cloud cell, only the areas with ascending flow should be targeted for seeding

- The atmospheric conditions, especially wind shears occurring with height, play an important role in cloud cell formation and rain production. At wind shears over 5-7 m/sec per 1km of height, the tops of cloud cells are “torn away” which impedes rain formation.

- The state-of-the art means for estimation of thermodynamic situation in the atmosphere enable to forecast the height of the top of a developing convective system. These atmospheric parameters being available alongside with on-line radar or/and aircraft data on the actual height of a cloud cell, make it possible to estimate its development status, i.e. whether the cell is under development or it has entered the stabilization or dissipation stage.

- Prior to seeding a massive cloud, it is necessary to estimate its cell development stage. The perimeter dimensions of the cloud are of minor importance, while its structure is of major importance (i.e., the pattern of distribution of ascending and descending flows and the total liquid content). In a cloud system, adjacent cells may undergo different developmental stages, “dying” cells being replaced by newly emerging ones.

- The analysis of experiments carried out in various climatic zones, among them in Penza, on Cuba, in Dnepropetrovsk, and Moldova showed that the maximum efficiency in seeding a convective cloud system is achieved when targeting growing cloud cells within the temperature ranges at the top being minus10^0C –minus 20^0C for maritime tropical clouds and minus 10^0C to minus 30^0C for continental clouds in moderate latitudes. The tops of such clouds in tropical areas are found at heights of 6.5-8 km, in continental areas (like Moldova or Ukraine) at heights of 5.5-9.5 km. In any case, the thickness of the overcooled section of a cloud cell should not be below 500 m. Seeding cloud cells at initial stages of their development, when the temperature at the top exceeded minus 10^0C, as well as at final stages with temperatures at the top dropped below minus 30^0C resulted in decreased seeding efficiency and sometimes even caused negative effects.

- Stratus cloud systems producing natural rain (Ns-As) are considered seeding-suitable in the case when they contain droplet or mixed layers not less than 50 m thick with temperature values below minus 4^0C.
- Air-mass Sc and St are considered seeding suitable in the case when they are of droplet structure, have temperature values below minus 4^0C , are not less than 500 m thick and have the lower boundary not exceeding 1000 m. As to Ac, their thickness must exceed 600 m.

There are requirements to be met in order to provide these rather complicated conditions, including special instruction for the staff performing cloud modifications and availability of certain technical means, both aircraft-mounted and ground-based, as well as a weel-developed methodology for radar follow-up of the experiments.

4 Seeding winter and midseason clouds in Moldova

Organization of operations

Using planes for exploratory investigation in winter and off-season cloud seeding in Moldova started in 1969, scientific research in winter-cloud rain enhancement commenced in 1984.

A large-scale field experiment was carried out in 1988-90 including seeding of cloud of various types by means of the Moldova Service planes together with those of CAO and the Ukraine Institute. In some sessions, up to 5 planes were simultaneously engaged.

The seeding-suitability of a particular cloud was established in accordance with the criteria worked out in Ukraine (see Sect. 2 above). According to the technology, different reagents should be used for seeding, among them refrigerants (artificial ice and liquid nitrogen) and glaciogens (AgI) with increased hydroscopic properties and various silver content. The choice of the reagent was determined by type and structure of a particular cloud, as well as the current atmospheric conditions.

Seeding efficiency was estimated with the help of radar precipitation station in the town of Kotovsk and on the basis of winter precipitation measurements carried out by Moldova hydrometeorological service.

The rain-enhancement bands were photographed from the screen of the MRL-5 radar mounted in Chisinau airport. The radar data on planes location and activities in the air, as well as on the structure of cloud and precipitation, were accumulated at the command post of joint air traffic control and air modification control. The data were transmitted to the cloud modification control officer on the plane board who selected seeding target areas within a cloud and made decisions on the appropriate procedure for the particular case.

The target area of 32-km radius, over which rain enhancement was planned, was chosen in view of precipitation control network location, its center being 32 km to the south-east of Chisinau in the village of Novo-Troyizkoye (Novo-Annensky district). Seedings were performed over the target area whenever a favorable situation emerged; otherwise, seeding was performed over other areas. The quantitative analysis of seeding efficiency was carried out on the basis of seasonal rain augmentation over the target in comparison with the long-term norms for this season and region.

5 Investigations of seeding potential

Air flights in Moldova were planned when one expected the arrival of frontal Ns-As clouds or well-developed frontal and air-mass Sc, St or Ac that do not produce natural rain. While a plane was ascending from the lower boundary of the cloud system to its upper boundary, the major parameters of the cloud were determined, namely: phase state, temperature, liquid water content, microphysical structure. In 1984, the total of 96 cloud probes were performed, involving 148 cloud layers. In most cases (81.8%) the probes were preformed within depression areas (cyclones, shallow gullies), while in 18.2% cases they were carried out in pressure spaces. The probes were aimed at estimating the seeding potential of a particular layer and the cloud system in general, the systems sometimes containing several layers of different types. A cloud system was considered to have a rain enhancement potential and, hence, to be seeding-suitable if at least one of its layers met the suitability criteria.

The studies showed that, despite an apparent homogeneity of many cloud systems, they often contained visually unobservable flooded convective cells, areas with steady ascending and descending motions, etc. The data presented in Table 3 show that frontal Ns-As and Ns systems studied as the experimental samples, were found to be seeding-suitable in 80% cases. This finding suggested a promising rain enhancement potential of seeding nimbostratus in Moldova, which, due to its geographic location, lay in the route of relatively young south and, especially, south-west cyclones of high water content.

Southern cyclones often slow down over the western part of the relatively warm and non-freezing Black Sea, getting additional water replenishment and thus increasing cloud liquid water content. These clouds are frequently suspended over Moldova and western Ukraine, staying longer over the target area.

Independent As cloud systems were observed only three times during the experimental period and were found seeding-unsuitable due to their crystallic structure.

Clouds that do not produce natural rain were found to be seeding-suitable on average in 33% of cases; in particular, the percentage is 25% for Ac, 35% for Sc and 33% for St.

Cloud form	Seeding-suitable clouds		Cloud not suitable for seeding		Total number of units	
	Number	%	Number	%	Number	%
Ns-As, Ns	24	80.0	6	20.0	30	100
As	-	-	3	100	3	100
Ac	2	25.0	6	75.0	8	100
Sc	12	35.3	22	64.7	34	100
St	7	33.3	14	66.7	21	100
Total	-	-	-	-	96	-

Table 3: Data collected on seeding-suitability of various cloud systems (one experimental unit is cloud probing within an individual operation flight)

In some cyclonic situations, quite unique cloud formations of high rainfall potential were observed. E.g., 22.12.1987, a powerful cloud system was formed in a cyclone rear within the secondary cold front effective area, composed of Ac (2,550-3,380 m), Sc (1,870-2,260 m) and Sc (1,130-1,280 m). Within the Ac layer, the mean temperature was below minus 12.8 ^{0}C and the mean liquid water content (MLWC) was found at 0.27 g/m^3. The upper Sc layer had the temperature of minus 7^{0}C and MLWC of 0.21 g/m^3.

The lower Sc layer had the MLWC of 0.25 g/m^3, the tempareture on its upper and lower boundaries being minus 3^{0}C and 0.4^{0}C, respectively. The total water content of this cloud system exceeded 500 g/m^2 . On the basis of probes, seeding-suitability of separate layers of the system was estimated (Table 4).

Cloud form	Seeding-suitable clouds		Cloud layers not suitable for seeding		Total number of units	
	Number	%	Number	%	Number	%
Ns-As, Ns	32	68.1	15	31.9	47	100
As	6	54.5	5	45.5	11	100
Ac	2	12.5	14	84.5	16	100
Sc	9	18.0	41	82.0	50	100
St	7	29.2	17	70.8	24	100
Total	-	-	-	-	148	-

Table 4: Seeding suitability of various cloud layers (one experimental unit being a single probe of cloud layer of a distinct type within a cloud system performed in an individual operation flight)

As can be seen from Table 4, cloud layers within Ns-As and Ns were found seeding-suitable in 68% cases. In comparison to Table 3, this fugure is 12% lower, since in some cases the analysis of Ns-As and Ns cloud systems revealed, for example, two layers, one seeding-suiatble and the other not. In such cases, the entire cloud system was considered seeding-suitable.

Layers As were found suitable for seeding only in 54.5% cases when they contained a mixed-phase layer with nucleating crystalls able to grow up to precipitation particles inside Ns cloud layers.

Ac layers were found seeding-suitable only in 12.5% of cases, Sc in 18% and St in 29% of cases.

As one can see, in comparison to cloud systems, seeding suitability of separate cloud layers is twice as lower for Ac and by 4% lower for St, which can be accounted for by the fact that Ac, Sc and St are often found in different combinations. For example, in a combination of two St layers, each 350 m thick, separated by 100-200 m-thick cloudless gap, a single St layer is considered not suitable for seeding due to insufficient thickness. As a system of 700 m total thickness, they are seeding-suitable, as the cloudless gap between them does not reduce the seeding effect.

The synoptic data suggest that seeding-suitable Ns-As and Ns most often emerge while passing warm fronts (58% of cases). Ac suitable for seeding were observed at warm fronts and secondary cold fronts, while seeding-suitable Sc mostly emerged at cold fronts (42%) and ridges (25%). St suitable for seeding were observed only in pressure spaces.

The upper boundary of seeding-suitable Ns-As layers that proved to be the main source of rain enhancement was measured in the following ranges:

1,510-3,000 m (57%); 1,010-1,500 m (22%); 3,010-4,500 m (21%).

The thickness of mixed-phase layers within Ns-As and Ns systems ranged between 100m and 2.000m, in two cases exceeding 2.000 m, in 26% of case ranging between 1,010-1,500 m, and in 18% of cases within 210-300 m.

Within As clouds, mixed layers had the thickness of 1,010-1,500 m (33%), in a single case exceeding 2,000 m, but most often ranging within 110-500 m. The thickness of seeding-suitable cloud layers was found to be within the following ranges: 610-900 m for Ac, 510-900 m for Sc, and 410-800 m for St.

The data on temperatures at the level of upper boundaries for seeding-suitable clouds are given in Table 5.

Type of cloud		Temperature ranges (^{0}C)								
		-4.0 ÷ -7.5	7.6 ÷ -10.0	10.1 ÷ -12.5	-12.6 ÷ -15.0	-15.1 ÷ -20.0	20.1 ÷ -25.0	25.1 ÷ -30.0	< - 30.0	Total
Ns-As Ns	N%	15 44.1	7 20.6	5 14.7	4 11.8	2 5.8	- -	- -	1 2.9	34 100
As	N%	- -	- -	2 33.3	- -	2 33.4	2 33.3	- -	- -	6 100
Ac	N%	1 50.0	- -	1 50.0	- -	- -	- -	- -	- -	2 100
Sc	N%	4 40.0	4 40.0	2 20.0	- -	- -	- -	- -	- -	10 100
St	N%	4 100	- -	- -	- -	- -	- -	- -	- -	4 100

Table 5: The recurrence of temperature values at the upper boundaries in seeding-suitable clouds of various types

The temperature at the upper boundaries of Ns-As suitable for seeding ranged within: minus 4^{0}C-7.5^{0}C (44.1%) cases; minus 7.5C-10.0^{0}C (20.6%) and minus 10.0^{0}C-20.0^{0}C (32.3% cases), only in one case dropping below 30.0^{0}C. At the upper boundary, the temperatures of seeding-suitable As layers were minus 10.0-25.0^0, and those of Ac, Sc, and St never went below minus 12.5^{0}C.

The data on the LWC the Ns-As layers is scarce since the measurements (Ms) were performed only when Il-14 planes were used. In 12 Ms, the mean droplet water content in the seeding-suitable layers was in the range of 0.06-

0.10 g/m^3, in one case reaching 0.11-0.15 g/m^3. High LWC of 0.41-0.45 g/m^3 in Ns-As was observed only once within 19 Ms.

The LWC values for As were found below 0.10 g/m^3(2 Ms) and for Ac (1 M) within 0.26-03 g/ m^3.

For Sc, in 2 Ms the LWC was below 0.05 g/m^3 and in 3 Ms it ranged within 0.26-0.30 g/m^3. Only 1 M of LWC in St was performed, the values ranging within 0.26-0.30 g/m^3.

In some experiments, the total water content (TWC) in clouds of different types was measured and found to be for Ns-As: within 6.0-10 g/m^2 (4Ms), 11-40 g/m^2 (4Ms) and 41-100 g/m^2 (1M). High TWC of 301-350 g/m^2 in Ns-As was observed only once within 13 Ms.

TWC. As was measured twice, the readings being 5 g/m^{2}and 31-40 g/m^2. The only Ms in Ac showed significant TWC in the range of 201-250 g/m^2.

In seeding-suitable stratocumulus, out of the total five Ms, two showed scarce TWC of 11-30 g/m^2, while in three Ms the values were much higher, ranging within 101-1250 g/m^2. Only one Mt was performed in St, TWC found was 101-150 g/m^2.

Although the sample considered above is not identical to the climatologic sequence due to irregularity of cloud modification activities, the data obtained present enough evidence to conclude that there are most favorable conditions for artificial rain enhancement in Moldova.

The first experimental series (1984-1988)

Seedings were performed if suitable clouds were located over the target area. In most cases, the seeding scheme was calculated so that the area of enhanced rain covered the north-west sector of the site. Artificial ice granules were used as reagents at the initial stage.

Similar to the experiments in Ukraine, large briquettes of carbon dioxide were crushed into small pieces on board of IL-14 or An-30 planes and dropped into the clouds using a special batcher, the doses being in the range of 300-700 g/km. In several experiments, certain lines were seeded with liquid nitrogen impregnating porous “airosila” granules being dropped from the plane by means of a batcher.

Liquid nitrogen dosage varied in the range of 50-650 g/km. In other experiments, silver iodide (AgI) was applied that was introduced into the clouds by means of PV-26 squibs each containing 1.5 g of AgI. The dosage depended on the air temperature and varied in the range of 2-6 g/km.

Below we consider the results of modification experiments involving 5 or more seeding lines, with duration exceeding 30 min.

Since Ns-As produce natural rain, their post-seeding enhancement is an indication of the increasing rate of rain production. When seeding Ac, Sc, St clouds, one can expect the commencement of artificial rain production, as clouds of these types do not produce natural rain.

Meteorological characteristics of Ns-As systems are presented in Table 6. The data show that the meteorological parameters of the seeded clouds varied within a wide range. The upper boundary heights were within the range of 990-3250 m, the thickness varied from 140 to 2050m, the temperature in the area of the upper boundaries ranged from minus 3.2 ^{0}C to minus10.3^{0}C. The drop water content values varied from 0.01 g/m^3 to 0.07 g/m^3, while the total water content did not exceed 84 g/m^3. These values for stratiform clouds indicate a low natural rain production rate. At the same time, large vertical extension of mixed-phase layers suggests that seeding these clouds may result in significant rain enhancement.

The seeding parameters for those clouds are presented in Table 7. Below, individual seeding sessions are considered in greater detail.

26.01.1984 experiment

Seeding was performed on multi-layer Ns, using CO_2 as the reagent, along the upper boundary of the Ns intermediate layer (1660 m, t= -3,2^{0}C), from an IL-14 plane. During 49 minutes, 6 lines were seeded, the dosages being: a) 1.200 g/km for 1st and 2nd lines; 2.600 g/km for 3rd line; 650 g/km for 4th line; 1000 g/km for 5th line, and 600 g/km for 6th line. The distance between the lines was 3 km. On the MRL-5 radar screen, during 15-20 min one could observe two faint but distinct lines of increased radio-echo against the background of light natural rainfall. The meteorologist on board the plane observed a significant consolidation of the cloud. The result obtained demonstrated that in some cases seeding lines can be seen on a radar screen even against the background of radio-echo from light natural rainfall.

10.02.1984 experiment

Seeding was performed in Ns clouds that had formed at the warm front of a south cyclone. The cloud system was a multi-layer one, Ns above the seeded layer were observed in the amount of 10 numbers. The Ns upper boundary was located at the height of 990 m, the temperature was minus 4.1^{0}C, the phase composition was mixed. 15 lines were seeded during 1 hour 29 minutes from an IL-14 plane, CO_2 dosage being 600 g/km. Intensive glaciation was observed within the seeded layer, while radio-echo from rainfall increased in power. Seeding-control officer registered significant rain enhancement.

Date	Synoptic situation	Type of clouds	H_{ub} m	ΔH, m	Temperature, centigrade		W, g/m^3	q, g/m^2	Phase structure	Wind speed m/sec	Comment
					H_{ub}	H_{lb}					
26.01.1984	WS SZn	Ns	1940	140	-5.3	-4.0	-	-	mixed	8	Layer with $t \leq -4^0C$ 1,810-1,940 m
		Ns	1660	310	-3.2	-2.1	-	-	mixed		
		Ns	1260	-	-	-1.8	-	-			
10.02.1984	WF S Zn	Ns	990	-	-4.1	-	-	-	mixed	15	intensive glaciation
25.01.1988	WF system	Ns	1440	1200	-9.1	-8.5	0.07	84	mixed	-	intensive glaciation
26.01.1988	WF with waves	Ns-As	1770	> 610	-8.4	-5.5	0.01	6	mixed	-	Ns-As above 1.770m are crystallic
27.01.1988	StF	Ns-As	2260	>2050	-10.2	-12.5	-	-	crystallic	7	Above 2,260 m the Ns-As layer is crystallic. Probing 14.41-15.15
27.01.1988	StF	Ns-As	1440	>1100	-8.3	-12.4	0.02	22	mixed	7	At 1,260-1,440 m, the layers are mixed. Beneath and above them – crystallic clouds. Probing 14.41-15.15
30.01.1988	WF system	Ns-As	3250	880	-9.9	-5.9	0.06	53	mixed	6	Beneath the seeded layer, Ns layer about 2,300 m. The plane did not descend below 2.370 m
31.01.1988	WF	Ns-As	2850	-	-6.5	-	0.01	-	mixed	-	The entire Ns-As-Cs system was located within the heights of 300-7,000 m
18.03.1988	CF	Ns-As	3150	300	-10.3	-9.5	0.02	6	mixed	-	Below 820 m: 3-5 Fmb numbers, their H_{ub} being 190 m
		Ns	2630	1810	-7.1	-2.9	0.04	72	mixed		

Table 6. Meteorological characteristics of clouds producing natural rain

Designations: Zn for cyclone; SZn for southern cyclone; Az for anticyclone; WS for warm sector; WF and CF for warm front and cold front; StF for stationary front; H_{ub} for the height of the upper boundary; H_{lb} for the height of the lower boundary; ΔH for the thickness of a cloud layer; W and q for the mean liquid water content and the mean total water content

Date	Type of cloud	H_{ab}, m	Seeding duration, hours.minutes	Δt, min	Rea-gent	P, g/km	n	L, km	l, km	Effect of modification	Comment
1	2	3	4	5	6	7	8	9	10	11	12
26.01.1984	Ns	1660	17.32-18.21	0.49	CO_2	600-2600	6	24	3.0	MRL registered two crystallization lines	
10.02.1984	Ns	990	12.33-14.02	1.29	CO_2	600	15	20	3.0	Significant increase in rainfall radio-echo power was observed	Seeding performed at the H_{ab} of a mixed layer, into Ns layer; intensive ice formation
25.01.1988	Ns-As	1440	17.25-18.24	0.59	CO_2	400	10	20	3.6	Significant increase in rainfall radio-echo power was observed	Meteorologist registered compression in the cloud within the seeded area.
26.01.1988	Ns-As	1770	13.11-13.54 13.56-14.22	0.43 0.26	CO_2	150 600	7 5	20 20	3.6 3.6	Significant increase in rainfall radio-echo power was observed	Meteorologist registered compression in the cloud within the seeded area.
27.01.1988	Ns-As	1150 (seeding level)	12.21-12.48 12.50-13.20	0.27 0.30	CO_2 CO_2	300 120	4 3	24 24	3.0 3.0	Significant increase in rainfall radio-echo power was observed	Meteorologist registered compression in the cloud within the seeded area.
27.01.1988	Ns-As	1440	15.08-15.27 15.29-16.13	0.19 0.44	CO_2 CO_2	300 100	3 7	20 20	3.0 3.0	Significant increase in rainfall radio-echo power was observed	Meteorologist registered compression in the cloud within the seeded area.
30.01.1988	Ns-As	3250	12.21-12.28 12.32-13.49	0.07 1.17	CO_2 CO_2	5000 500	1 9	30 30	12.0 3.5	MRL registered radio-echo bands reflected from artificial rain that were reaching the ground (against the background of natural precipitation of I_e – 1mm/h)	Between line 1 and line 2, L=12 km. During 80-90% of the time seeding was performed inside a mixed layers.
31.01.1988	Ns-As	2850	13.57-14.00 14.05-14.14 14.17-14.22 14.24-14.44	0.03 0.09 0.05 0.20	CO_2 CO_2 CO_2 CO_2	1250 600 400 100	1 1 1 4	20 20 20 20	8.0 5.0 5.0 4.0	Meteorologist registered compression in the cloud within the seeded area.	Manual CO_2 drop. ADG –1 graining batcher
18.03.1988	Ns-As	2630	14.39-15.11 15.19-15.39	0.32 0.20	N_2 CO_2	560 300	5 3	20 20	3.6 3.6	Meteorologist registered compression in the cloud within the seeded area.	Seeding inside a mixed layer. Favorable seeding conditions maintained. Meteorologist registered compression in the cloud within the seeded area.

Table 7. Physical parameters of seeding clouds producing natural rain

Designations: H_{ab} for the height of the upper boundary; Δt duration of seeding; P- dosage of reagent; l – distance between seeding lines

25.01.1988 experiment

Cloud parameters and seeding conditions are presented in Tables 6 and 7. Seeding was performed within Ns-As layer inside the cloud system along the upper boundary of the suitable layer, CO_2 dosage being 40 g/km. 10 lines were seeded, each line 10 km long, the distance between the lines being 3.6 km. The conditions were most seeding-favorable. The meteorologist on board the plane observed significant cloud consolidation within the seeding area; the power of radio-echo from rainfall increased.

26.01.1988 experiment

Seeding was performed within Ns-As system that had formed at the warm front, the suitable layer was located at the height of 1,770 m. The temperature within the seeding area was minus 8.4^0C, drop water content in the seeded layer being $0.01 g/m^3$. Above the seeded layer, crystal Ns-As were observed. During the seeding time, the CO_2 dosage varied from 150 to 600 g/km. Radio-echo on the radar screen resembled crystallization bands 20-25 km long. In the same sector, the radar registered rain augmentation of about 0.1 mm.

27.01.1988 experiment

Seeding was performed within a Ns-As crystal system at the height of 1,550m, at the temperature minus 10.2^0C. The cloud system had formed at the stationary front. Seeding was performed against the background of natural rainfall at 12.21-13.20, the CO_2 dosage being 300 g/km (4 lines) and 120 g/km (3 lines). An increase in the radio-echo power was observed.

On the same day, another seeding was performed at 15.08-16.13. By this time, a seeding-suitable layer had formed in the cloud system, its upper boundary at 1,440m with the temperature of minus 8.3^0C, while the temperature at the lower boundary of the layer at the height of 340 m was minus 12.4^0C. The layer was of mixed-phase type, MLWC of $0.002 g/m^3$. These conditions are considered highly favorable for cloud seeding, which in this case resulted in a significant radio-echo increase.

30.01.1988 experiment

Seeding was performed within Ns-As cloud that had formed at the warm front. The multi-phase layer was at the height of 2,430-3,250 m, its MLWC being $0.06 g/m^3$ and the total water content $53 g/m^2$. The temperature at the upper boundary of the layer was minus 9.9^0C; 10 numbers of loose As-Cs clouds were located above the seeding height. Totally, 10 lines, each 30 km long, were seeded with solid CO_2 at the dosage of 500 g/km (1^{st} line was seeded at 12.21-12.32; from 12.32 till 13.49 9 lines were seeded; 2^{nd} line that was located 2 km away from the 1^{st} one; the remaining 8 lines were located at the distance of 3.5 km from each other).

At the conic radar section performed at 13.11 (Fig. 3), one can see band structures corresponding to the crystallization zones of the seeded parallel lines. Later, MRL-5 registered a distinct zone of enhanced rainfall, which confirmed the success of the seeding.

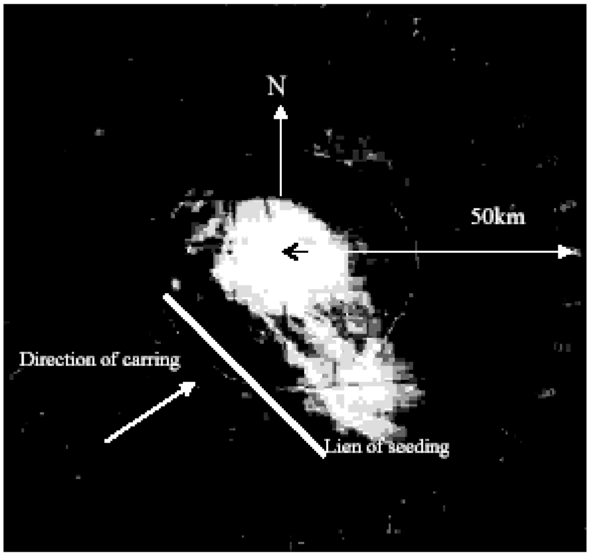

Figure 3: Photo of enhanced rain radio-echo (the city and the airport of Chisinau, 13.01.1988, 13:11).

31.01.1988 experiment

Seeding was performed within Ns-As cloud system that had formed at the warm front. A multi-phase layer was seeded at the height of 2,850 m, the temperature within it being minus 6.5^0C, with total water content of 0.01g/m^3. Totally, 7 lines were seeded at different dosages of solid CO_2 (the values shown in Table 7). The radar did not detect seeding lines against the background of strong natural rainfall (the rate ranging within 0.6-1.2 mm/h). At the same time, similar to other seeding sessions, a significant increase in radio-echo power was registered from the seeded zone, where the meteorologist aboard the plane observed significant cloud consolidation.

18.03.1988 experiment

Seeding was performed within Ns-As cloud system that had formed at the cold front, where two seeding-suitable multi-phase layers were found, the lower layer at the height of 2.630 with the temperature of minus 7.1^{0}C. The MLWC in the layer was 0.04 g/m, with the total water content of 72g/m^2 . Most of the lines were seeded with liquid nitrogen at the dosage of 50g/km. 3 lines were seeded with solid CO_2 at the dosage of 300 g/km. The radar registered an increase in radio-echo-power.

In should be noted that modification of nimbostratus, both in Moldova and Ukraine, demonstrated that a radar is frequently unable to register objective evidence and/or perform accurate quantitative estimation of rain augmentation. At the same time, the precipitation network does register a significant relative rain augmentation (up to 30-100% and more) in cases when seeding is performed appropriately.

The next section describes the experiments performed within the same period on seeding clouds that did not produce natural rain. Totally, five sessions were performed involving seeding of 5 or more lines, the meteorological parameters of the clouds being presented in Table 8, and the seeding data presented in Table 9.

25.02.1984 experiment (3 seedings)

During the day, opaque St clouds were observed over central Moldova, that had formed at the south-western periphery of an anticyclone.

Seeding # 1 was aimed at checking the radar's ability to detect crystallization lines and enhanced precipitation after seeding the clouds with AgI. The operation started at 11.30, when Yak-40 plane seeded 3 lines, each 25 km long, the distance between the lines being 4.9 km. The seeding was performed from the height of 100 m over the upper cloud boundary with the help of PV-26 squibs.

On 1st and 3rd lines, the distances between squib shoots were 400 m at the dosage of 4 g/km. On the 2nd line, the dosage was 2 g/km and the distance between squib shoots 800 m. 1st and 2nd lines were seeded to the south-east of Chisinau, at the distance of 10-13 km from the city airport; 3rd line seeded to the north of the airport at the distance of 10 km.

At the time of seeding, the clouds had the following parameters: upper boundary at 1,230 m, lower boundary at 830 m, the temperature at the boundaries being minus 7.2^{0}C and minus 6.9^{0}C, respectively; thickness 400 m.

Date	Synoptic situation	Type of cloud	H_{ub}, m	ΔH, m	Temperature, centigrade		Liquid water content W, g/m^3	Total water content q, g/m^2	Phase state	Wind		Comment
					H_{ub}	H_{tb}				directionp (degrees)	speed, m/sec	
25.02. 1984	Az ridge	St op	1050	700	-4.2	-	-	-	droplet	140	7	
22.12. 1984	South-east Az periphery	St	920	370	-9.3	-8.6	-	-	droplet	120	5	
01.03. 1987	CF	Ac op	2550	450	-10.5	-10.5	-	-	droplet	280	17	
		Sc op	1250	570	-9.5	-6.5	-	-	droplet			
22.12. 1987	Zn rear	Ac op	3380	830	-12.8	-9.5	0,27	224	droplet	350	12	Probe time 09.42-11.25
	Secondary CF	Sc	2260	390	-7.0	-5.7	0,21	82	droplet			
		Sc op	1280	850	-3.0	-0.4	0,25	212	droplet			
22.12. 1987	Zn rear	Ac	3480	180	-14.1	-13.1	-	-	droplet	360	12	Probe time 13.11-14.25
	Secondary CF	Ac	2920	300	-10.2	-9.1	0,18	54	droplet			
		Sc op	910	400	-1.6	1.4	0,36	144	droplet			

Table 8. Meteorological characteristics of clouds not producing natural rain
Designations are the same as those for Table 6.

Date	Type of cloud	H_{ub}, m	Seeding duration, hours.minutes	Δt, min	Rea-gent	P, g/km	n	L, km	l, km	Effect of modification	Comment
1	2	3	4	5	6	7	8	9	10	11	12
25.02.1984	St op	1050	14.52-14.55 15.03-15.08 15.16-15.20 15.22-15.45	0.03 0.05 0.04 0.23	N_2 CO_2 N_2 CO_2	50 600 100 350	1 1 1 4	12 20 16 20	3.0 3.0 3.0 3.0	MRL detected all the seeding lines and photo-registered them. Intensive rainfall over vast territory including Chisinau airport	Horizontal visibility within artificial rain below 500m; Chisinau airport has been closed
22.12.1984	St	920	13.23-13.50	0.27	AgJ	6,0; 3,0 1,5; 6,0 0,75	5	20	3.6	MRL detected the first 4 lines, 1st and 4th lines being especially distinct, their radio-echo was followed down to the ground.	Rainfall caused by the seeding is reaching the ground
01.03.1987	Ac op	2550	07.54-08.23	0.29	CO_2	600	5	20	4.5	MRL detected 4 lines and rainfall reaching the ground. Significant rainfall enhancement.	Below Ac there is Sc op layer (see Table 4)
22.12.1987	Ac op Sc op Sc op	3380 2260 1280	09.59-11.10	1.11	CO_2	350	10	20	3.2	MRL detected radio-echo zones reflected from intensive rainfall reaching the ground. (27decibel at the distance 25km)	
22.12.1987	Ac	3480	13.55-14.07 14.09-14.22	0.12 0.13	CO_2 N_2	350 600	3 3	16 16	3.0 3.0	MRL detected e lines. Rainfall not reaching the ground. MRL detected the first 2 lines. 3rd line seeded along the edge of thin Ac was not detected by the radar.	

Table 9. Physical parameters of the experiments in seeding clouds not producing natural rain
Designations are the same as those for Table 7.

Visual observations showed intensive glaciation within the clouds and formation of 3 crystallization bands, 2 km wide each, that did not merge into a common zone. The radar registered all 3 lines of the enhanced rain, radio-echo from them reaching the ground. Later, the decrease in the boundary heights (upper boundary down to 1,050 m, lower boundary down to 290 m) was registered, together with a temperature rise at the boundaries (up to minus 4.2^0C and minus 6.5^0C, respectively). The probe registered an increase in cloud thickness up to 760 m. The temperature minimum of minus 7.0^0C was registered at the height of 950 m.

Seeding # 2 was performed from IL-14 plane at 14.52-15.45, with 7 lines seeded. 1^{st} line 12 km long and 3^{rd} line 16 km long were seeded with liquid nitrogen introduced into clouds within porous "aerosila" granules, the plane flying at 100 m, i.e. 50 m below the upper cloud boundary. N_2 dosage on 1^{st} line was 50 g/km, on 3^{rd} line 10 g/km.

Other 5 lines, 20 km long each, were seeded with solid CO_2, the dosage being 600 g/km on 2^{nd} line, 350 g/km on lines 4-7.

The action was carried put at 20-25 km to south-east from Chisinau airport, the windspeed within the cloud being 140^0 -7m/sec. It was expected that the enhanced rain area would cover the city of Chisinau and the territory of the airport.

The seeding resulted in intensive enhanced rain. Over the airport, the horizontal visibility reduced down to 400-500 m, causing the airport closure and changing the routes of 7 heavy passenger planes.

The modification effect is well observed on photos of the radar screen. Fig. 4 shows a conic section performed at 15.56, displaying 5 distinct band of enhanced rainfall. 1^{st} line (on the left, close to the center of the circle) and 3^{rd} line are the result of N_2 seeding, while 3 lines were formed by solid CO_2 seeding.

The remaining two lines had not yet been formed by the time of photographing. Thus, seeding St with two reagents resulted in artificial rainfall. Radar observations showed that the zones of crystallization and enhanced rain formed by liquid N_2 and those produced by solid CO_2 seeding were practically alike, while liquid N_2 dosage was by factor of 3-12 lower that that of solid CO_2 (Table 9.)

Seeding # 3 was performed on the same cloud system at 15.19-15.38 at the distance of 20-25 km to the north-west of Chisinau. 3 lines, 25 km long each, were seeded with AgI from Yak-40 plane (1^{st} line at dosage of 4 g/km, 2^{nd} and 3^{rd} lines at dosage of 2 g/km, the distance between the lines being 5 km).

According to probe readings, the upper boundary of St was at 1,190 m,

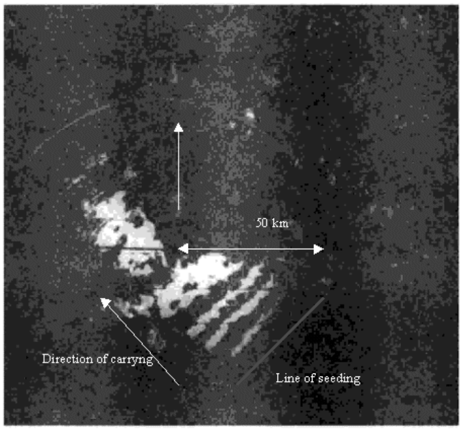

Figure 4: Horizontal section of seeding area (25.02.1984; 15:56). The white streaks and broadening spots represent rain enhancement radio-echo.

the lower one at 370 m, the temperatures being minus 8.6^0C and minus 7.2^0C, respectively. Visual observations revealed strong glaciation, as well as formation of 3 crystallization bands, each about 2 km wide. Intensive rainfall was observed from the plane.

Seeding was performed in St system formed at the south-west periphery of an anticyclone. Droplet clouds were located within 500-920 m layer, the temperatures being minus 8.6^0C and minus 9.3^0C, respectively. Strong glaciation was observed.

22.12.1984 experiment

Seeding was performed at 13.23-13.50 with AgI (PV-26 squibs), on 5 lines 20 km long each, the distance between the lines being 5 km. The dosages were: on 1^{st} and 4^{th} lines 6 g/km, the distance between squib shoots 250 m; on 2^{nd} line 3 g/km; on 3^{rd} line 1.5 g/km; on 5^{th} line 0.75 g/km, the distance between squib shoots 2,000 m.

According to visual observations, zones 1 and 4 were more distinct, being continuous and of about 2.6 km width. Zone 2 was also continuous, converging here and there down to 1 km. Line 3 was not continuous, and line 5 consisted of separate crystallization sites that did not merge.

The radar registered 4 lines, lines 1 and 4 being more distinct, radio-echoes from them traced down to the ground. Lines 2 and 3 were feebly marked as consisting of separate sites. Line 5 was not registered by the radar at all.

The results of this session show that distinct zones of enhanced rain were formed only when the distance between squib shoots was 250 m and the dosage 6g/km.

01.03.1987 experiment

Seeding was performed within Ac cloud system that had formed at the cold front. Droplet clouds were located at 2,100-2,550 m, the temperatures at both heights being minus 10.5^{0}C, strong glaciation within the clouds was observed. Sc layer was located beneath Ac layer, its lower boundary at 680m, upper boundary at 1,250 m, the temperatures being minus 6.5 ^{0}C and minus 9.6^{0}C, respectively.

Seeding was performed from An-3 plane on 5 lines, 20 km long each, the distance between the lines 4.5km, with solid CO_2 at the dosage of 600 g/km.

The radar registered 4 lines of enhanced rain, their radio-echo reaching the ground. 1st line was not radar-registered, which can be accounted for by the fact that it was seeded within loose clouds with openings.

22.12.1987 experiment (2 seedings)

Seeding # 1 was carried out within a three-layer cloud system that had formed at the secondary cold front located at the distance of 150-200 km from the cyclone center. The upper Ac layer was at the height of 2,500-3,380 m, the temperatures being minus 9.5 ^{0}C and minus 12.8^{0}C , respectively. The thickness of this layer reached 830 m. The MLWC and TWC were 0.27 g/m^3 and 224 g/m^2, respectively.

Beneath this layer, there were two Sc layers. The first Sc layer was located within the heights of 1,870-2,260 m, with respective temperatures of minus 5.7^{0}C and minus 7.0^{0}C. The layer was 390 m thick, its MLWC and TWC were 0.21 g/m^3 and 82 g/m^2, respectively. The second Sc layer, i.e. the lowest one in the system, was located within the heights of 430-1,280 m, with respective temperatures of minus 0.4^{0}C and minus 3.0^{0}C. The layer was 850 m thick, its MLWC and TWC were 0.25 g/m^3 and 212 g/m^2, respectively.

The entire system provided highly beneficial conditions for rain enhancement since the inter-cloud strata were thin (290 m between the upper layers and 570 m between the lower layers), the total thickness of the cloud system being 2,070 m and its TWC 518 g/m^2.

The seeding of the potent upper layer would most likely lead to an increase of enhanced rain particles in the lower layers, while evaporation losses in the cloud-topped boundary layer were most unlikely due to the low height of the lower cloud boundary (430 m).

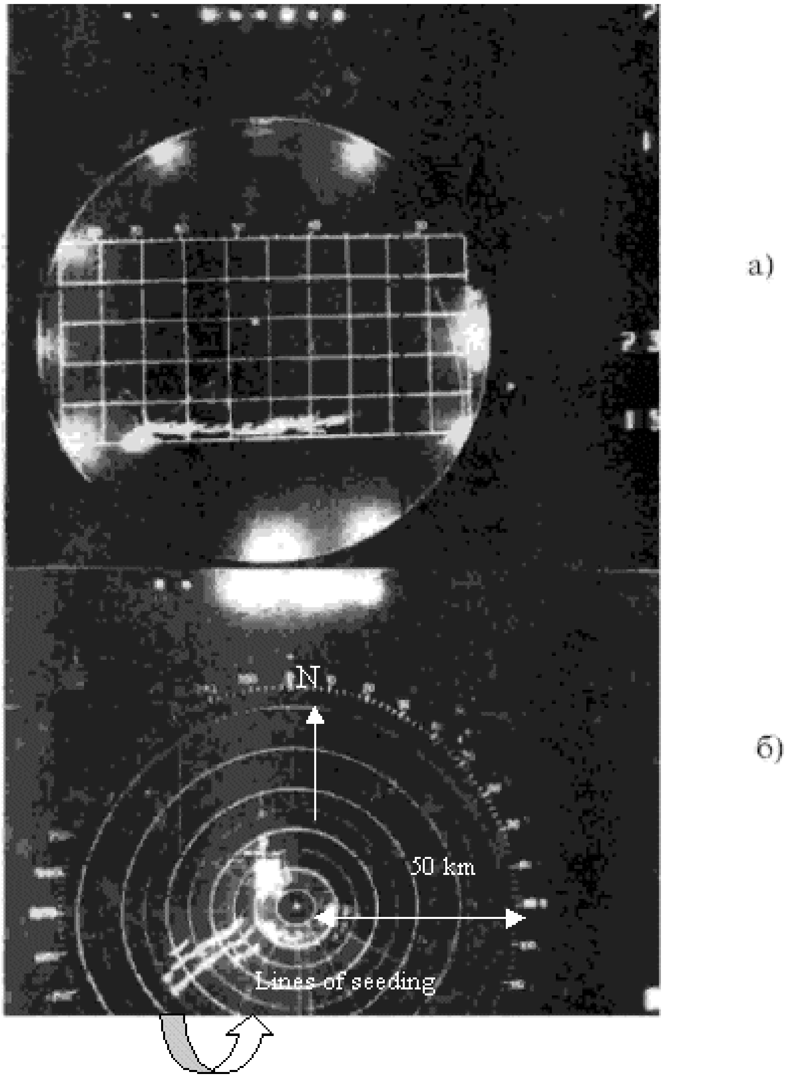

Figure 5: Sections of radio-echo over the seeding area (22.12.1987; 10:50) vertical section, horizontal section.

Seeding was performed on the upper Ac layer from IL-14 plane with solid CO_2 at the dosage of 350 g/km, at the upper boundary height of 3,380 m. within 1 hour 11 min (09.59-11.10) 10 lines, 20 km long each, the distance between the lines being 3.2 km.

The operation resulted in intensive rain enhancement occurring at 10.50-

13.30, i.e. during 2 h. 40 min., which was twice as long as the seeding duration (1h. 11 min.) The efficiency of the seeding was confirmed by radar observations. MRL-5 radar positioned at Chisinau airport performed conic and vertical sections of the clouds and the precipitations they produced. Another radar that was a part of the precipitation network was located in the town of Kotovsk and measured precipitation.

The vertical section performed at 10.50 (Fig. 5a) shows the artificial rainfall zones at the moment when the precipitation is reaching the ground, which was considered the commencement of the rainfall. Fig. 5b shows the conic section performed at 10.57, showing 4 lines of radio-echo from the artificial rainfall.

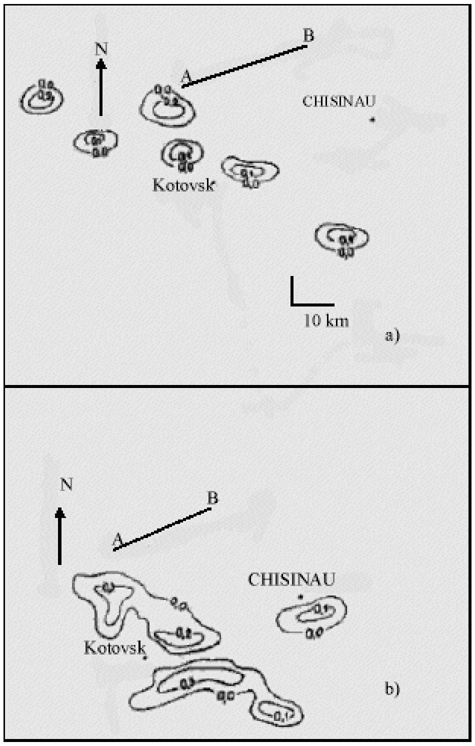

Figure 6: Isolines of equal rainfall rate (mm/h; radar data on 22.12.1987). a) 10:10-10:15; b) 10:55-11:00.

Fig. 6a shows the data obtained on the second radar at 10.10-10.15 while the rain had not yet been formed, several small spots being the ground clutter echoes. The cloud modification rout is marked in this figure, as well as in the next figures, with AB line. As can be seen in Fig. 6(b), presenting the summed-up situation at 10.55-11.00, the rain is already falling, its maximum rate in the centers of the zones reaching 0.33 mm/h which is indicated by isolines marking equal rainfall rates.

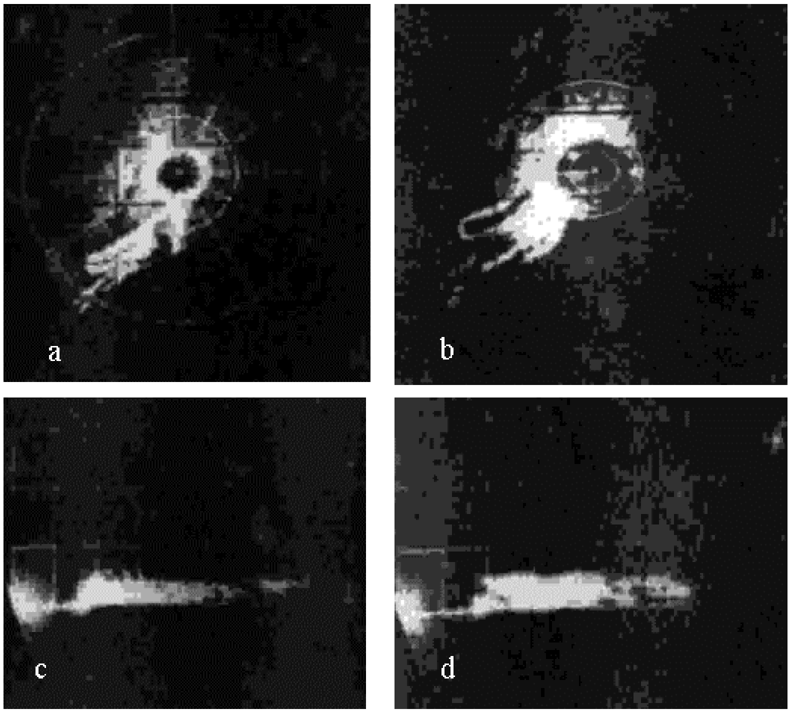

Figure 7: Photo of rain enhancement radio-echo (22.12.1987). a) horizontal section at 11:22; b) horizontal section at 11:45; c) vertical section at 11:25; d) vertical section at 11:49.

In the development, the crystallization zones expanded and artificial rain production intensified. Fig.7 (a,b) shows conic sections of radio-echoes from the seeded clouds at 11.22 and 11.45, respectively, presenting the development of the crystallization zones in space and with time. Initially, the lines were 2.5- 3 km wide, while at 11.45 they merged forming a vast rainfall area. Fig. 7(c,d) show vertical sections of the artificial rain radio-echo at 11.25 and 11.49, respectively, illustrating evolution of the vertical structure of the powerful crystallization zone and intensive rain. The upper boundary of the radio-echo is at the height of 3.5 km, the lower boundary on the ground level. In the right parts of the figures, one can see crystallization zones of the last three seeded lines which are just starting to merge, artificial rainfall from them not yet reaching the ground.

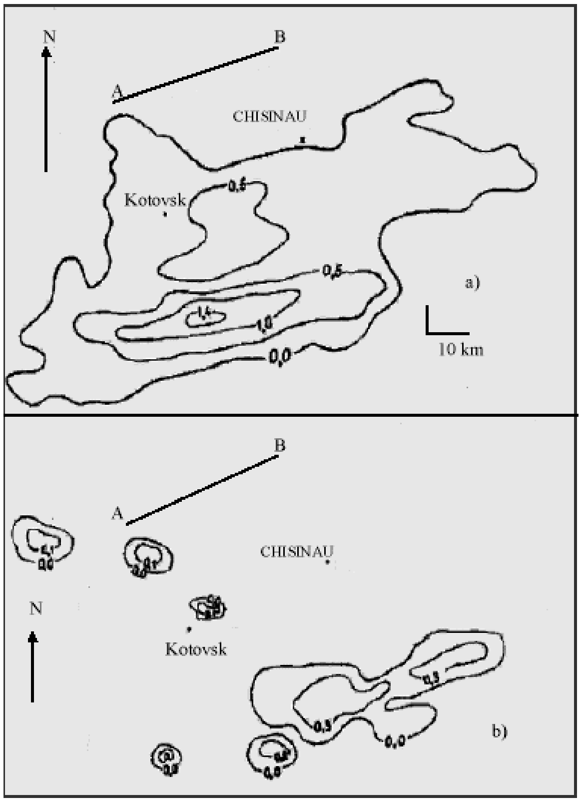

Figure 8: Isolines of equal rainfall rate (mm/h; radar data on 22.12.1987). a) 12:05-12:10; b) 13:20-13:25.

At 12.05-12.10 the rain area expanded drastically (Fig. 8a) having reached the area of 1000 km^2, while the rain rate reached 1 mm/h in the central part of the zone and even 1.4.mm/h in the very center.

The artificial rain area expanded drastically due to a change in the wind shear and reached the length of 50 km (along the seeding line) and the width of 45-60 km. The square of the precipitation area exceeded 2,000 km^2. The zone within the 1mm/h isoline had the size of 24 km x 15 km, its nucleus (rain rate of 1.5 mm/h and more) being 12 km x 6 km.

As soon as the seeding was over after 13.00, a gradual decrease in the artificial rain rate was observed. In Fig. 8b obtained at 13.20-13.25 in Kotovsk region, only ground clutter radio echo lines can be seen, while the area of radio echo from the rain had shrunk down to 600 km^2, the rain rate in the center not exceeding 0.3 mm/h. The last rainfall site of 0.0-0.2 mm/h rate of about 100 km^2 square was observed at 13.00-13.35 to the south of Chisinau.

The data presented in the figures show that seeding the potent multi-layer cloud system resulted un intensive artificial rain, covering the area of 600-3,000 km^2. The seeded cloud square was of 800 km^2 (20 km x 40 km). High total thickness of the cloud system (2,070 m) and its high TWC (518 g/m^2) together with its cyclonicity were the main factor providing the high seeding efficiency. In this particular case, clouds that otherwise would not produce rain responded to seeding and produced rain at the mean rate of 2.0-2.5 mm/h, total duration of 2h. 40 min, covering the average square of 1000 km^2.

Seeding # 2 was performed in the rear of the same cloud system 3 hours after the first seeding. By this time, the main bulk of the clouds had left the seeding site, with two thin Ac layers remaining. 1st layer was located at the heights of 3,330-3,3480 m, the boundary temperatures being minus 13.3^{0}C and minus 14.1^{0}C, respectively. 2nd layer was located at the heights of 2,260-2,920 m, the boundary temperatures being minus 13.3^{0}C and minus 14.1^{0}C, respectively, and had LWC of 0.18 g/m^3 and TWC of 54 g/m^2.

Both Ac layers were of a droplet type, with moderate glaciation observed within the upper layer and feeble ice formation within the lower one.

The lowest Sc level of the initial cloud system was still existing, located at the heights of 510-910m, the boundary temperatures being 1.4^{0}C and minus1.6^{0}C, respectively, and having LWC of 0.36 g/m^3 and TWC of 144 g/m^2 .

The clouds were seeded with solid CO_2 (3 lines 16 km long, the dosage of 350 g/km) and N_2 (3 lines 16 km long, the dosage of 600 g/km). The MRL-5 radar registered two crystallization bands following the CO_2, however, the rain did not reach the ground. No other bands were registered, since the lines were seeded along the edge of the cloud layer where the clouds were extremely thin.

The clouds seeded in this experiment were not seeding-suitable.

To sum up, three kinds or reagents were used in cloud seeding in the above-described experiments: solid CO_2, liquid N_2, and AgI. The results demonstrate that when cloud temperature does not exceed the threshold for a particular reagent's efficiency (i.e.minus 4.0^{0}C for CO_2, N_2 and minus

7.0^0C for AgI), seeding is always efficient provided the cloud layer thickness and TWC values are within the required range.

At the same time, the experiments point out at the necessity a careful estimation of the parameters involved in rain formation in every particular case, before making a decision as to cloud's seeding-suitable and the expected level of seeding impact. Otherwise, seeding of cloud layers and cells may yield a zero effect.

The second experimental series (1988-1990)

In 1988-1990 a series of field experiments were performed in Moldova over the target area as in the first series, while differing in several aspects:

- more frequent seeding, taking advantage of most of the favorable settings and situations;
- priority given to seeding those clouds that were expected to precipitate over the target area;
- taking into account wind shears;
- using, instead of briquettes, carbon dioxide granules of strictly defined dimensions (length and diameter) produced from liquid carbonic acid by means of a specially designed granulator. The dimensions of the granules in combination with their extremely low own temperature allowed them in winter to seed lines not less than 500 m long (in super-cooled liquid droplet medium);
- using liquid nitrogen directly within the super-cooled cloud section. Unlike previously used porous corpuscles saturated with N_2, in our experiments liquid N_2 was introduced into the super-cooled droplet cloud section immediately from the Dewar vessels via special outboard jets;
- flexible approach to combining various reagents, such as carbon dioxide granules, liquid N_2, Ag squibs, etc. in accordance with particular seeding conditions;
- assessing seeding results by comparing the annual average rate (calculated for a particular period) of rainfall over the target area with the normative annual average rainfall rate over the target and surrounding territory.

Rainfall measurements were performed by means of a radar station and the hydrometeorological service equipment.

Unfortunately, economic instability in Moldova commenced exactly at the time of the field experiments. Due to frequent interruptions in plane fuel supply, only 30% of potentially seeding-suitable situations were actually taken the opportunity of.

In the periods of November 1988-April 1989 and November 1989-April 1990, the number of rainfall days was 214, the modification was carried out 127 times. The total seeding-suitable time over these two periods was calculated at 2,374 hours, while only 750 hours were actually used for seeding. The average layer precipitated over the target area during this period was 375 mm (189 mm in 1988, 116 mm in 1989, and 70mm in 1990). The mean rain augmentation, in comparison with the long-term norms for these regions, was, respectively, 16.8%, 13.8%, and 15.3%; in comparison with the mean values for these years, it was calculated at 15.2%, 17.3 %, and 22.0%.

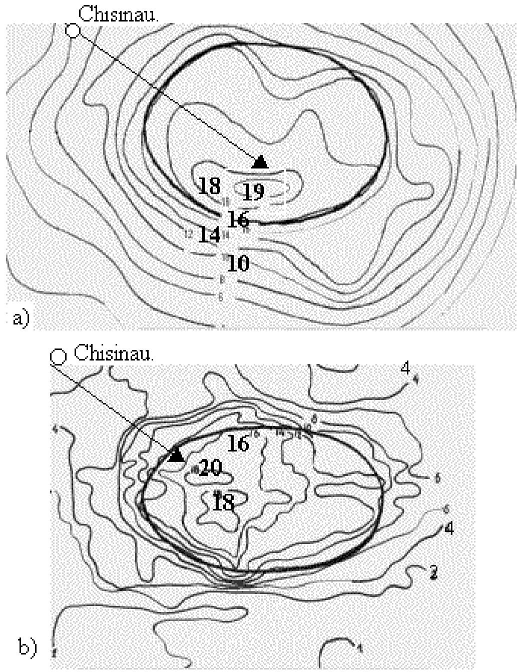

Figure 9: Isohyets of rain quantities over two periods. a) November 1988 - April 1989; b) November 1989 - April 1990.

The normative rainfall rains for the said periods were calculated by the data on the rainfall that had precipitated over a number of districts surrounding the target territory.

Fig. 9 presents isohyets of rain quantities over the periods. It is noteworthy that close to the center of the target area there is a “nucleus” of maximum rain augmentation. It is most unlikely that such a “nucleus” could be formed over a preset area in case of natural rainfall, hence the presented isohyet pattern can be accounted for by the effects of the seeding.

It is most likely that the results could have been higher if there had been the opportunity of using more seeding-suitable situations.

6 Conclusions

The exploratory and field experiments carried out during many years in Moldova and Ukraine aimed at enhancing rain from clouds of various types lead to the following conclusions:

Within St, Ns, As, Sc, and clouds of other known types, despite their apparent homogeneity, there are always flooded (embedded?) by convective cells, areas of steady ascending and descending motions, etc, often non-observable visually.

Regardless the characteristics of the target terrain, the technology of seeding for rain enhancement must take into account the comprehensive picture of rain-forming processes, among them the structure and evolution stages of a particular cloud at the time-instance of seeding. Seeding reagents are to be introduced precisely into a selected cloud layer whose parameters are appropriate for the microphysical transformations producing rain, i.e. crystallization of droplet water and an abrupt increase in crystal concentration by 1-2 orders of magnitude. It was also shown that violation of this principle reduces seeding efficiency to the levels that make it economically irrelevant.

Seeding clouds (cloud cells) may result in effects different both in volume and sign, depending on the cloud evolution status at the time instance of seeding. Therefore, any modification should be preceded by a snap analysis of cloud situation by means of a radar or/and probes immediately in the cloud in question.

Seeding equipment and the reagents should enable the maximum seeding efficiency depending on the current state of a cloud system. Various cloud processes may develop in different areas within the same cloud system, e.g., stratus and convective systems simultaneously formed. In situation like that, it appears most efficient to use carbon dioxide granules for seeding upper boundaries of the convective layers and AgI squibs for seeding the convective cells. In some situations, seeding clouds via their lower boundary may be most effective.

The maximum efficiency in seeding a convective cloud system is achieved when targeting growing cloud cells within the temperature ranges at the top being minus10^0C – minus 30^0C (for conditions in Moldova). The tops of such clouds in continental areas of Moldova or Ukraine are at heights of 5.5-9.5 km. In any case, the thickness of the overcooled section of a cloud cell should not be below 500 m. Seeding cloud cells at initial stages of their development when the temperature at the top exceeded minus 10^0C, and especially at the final stages with temperatures at the top below minus 30^0C, resulted in decreased seeding efficiency and sometimes even caused negative effects.

Stratus cloud systems producing natural rain (Ns-As) are considered seeding-suitable if they contain droplet or mixed layers not less than 50 m thick with temperature values below minus 4^0C.

Air-mass Sc and St are considered seeding suitable in case they are of droplet structure, have temperature values below minus 4^0C, are not less than 500 m thick and have the lower boundary not exceeding 1000 m. As to Ac, their thickness must exceed 600 m.

There are requirements to be met in order to provide these rather complicated conditions, including special instruction for the staff performing cloud modifications and availability of certain technical means, both aircraft-mounted and ground-based, as well as a well-developed methodology for radar follow-up of the experiments.

Provided the above formulated requirements are met, the efficiency of cloud seeding depends on regional synoptic conditions for a particular season. E.g., climatic conditions in Moldova are highly favorable for significant rain enhancement all the year round, enabling to reach augmentation up to 25% in summer and up to 20% in other seasons.

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