HAIL SUPPRESSION ACTIVITIES IN THE SOVIET UNION

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Hailstorm modification activities to prevent hail damage have been carried out in the Soviet Union for more than 15 years. Great interest to the national economy and high benefit-to-cost ratio of the hail protection program have motivated a considerable increase in the volume of hail suppression operations in the USSR.

Ten hail suppression divisions are currently operating in the Soviet Union. They comprise 53 groups (detachments). In 1979, these detachments protected crops from hail damage over an area of 6.5 mln ha. Results of hail suppression projects during the period 1975 to 1979 are presented in Table 1. Analysis of the hail protection results show that on the average, crop losses due to hail in the protected area have been reduced by more than 70 percent as compared with the many years' average damage and the losses in the control areas. The cost of the crop being preserved amounts to the sum of tens of millions of roubles.

However, we are still far from completely solving the hail problem, in spite of the fact that considerable progress has been made towards the solution of it in the last few years, since in some cases damaging hail is observed over the protected area. Reliable hail protection is the most complex problem in case of the development of very severe hail clouds.

A special research and experimental site (polygon) instrumented with a modern radar and meteorological equipment has been set up in the North Caucasus to study meteorological and aerosynoptical conditions of the formation and development of very severe hail clouds, as well as investigate the process of hail formation and growth in clouds, and improve the existing techniques of artificial modification of hailstorms of various intensities.

Recent studies by the Soviet scientists (Abshaev M. T., Bibilashvili N. Sh., and others) made it possible to more accurately define the spacial structure of hail cores in a cloud, the location of hail initiation, and the area and structure of updrafts, as well as to measure the period of hail core formation and the velocity and direction of their motion. Experiments on hail cloud modification aimed at their suppression showed that seeding should be done in the early stage of hail formation (when conditions are formed for hail initiation) rather than in the hail growth stage as it was suggested earlier. At this stage, it is much easier to achieve positive results from seeding with crystallizing reagents, making the most use of the effect of unstable equilibrium of a supercooled waterdrop cloud and stimulating premature (prior to hail formation) rainfall. Injec-

TABLE 1

RESULTS OF ANTI-HAIL PROJECTS IN THE USSR (1972-1979)

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Region of project	1972		1973		1974		1975		1976		1977		1978		1979	
	TA	EC	TA	EC	TA	EC	TA	EC	TA	EC	TA	EC	TA	EC	TA	EC
Caucasus	446	44	435	99	441	66	490	66	484	46	631	60	600	84	600	92
Krasnodarsky region	520	82	540	61	540	83	542	67	458	87	575	50	625	59	635	73
Ukraine SSR	110	100	210	91	210	82	210	82	275	88	390	99	390	99	395	99
Uzbekistan	243	92	282	81	282	94	300	100	300	89	400	98	410	80	500	97
Georgia	250	95	250	97	250	87	350	99	350	95	350	98	380	97	400	94
Azerbaijan	320	100	447	86	447	92	570	99	737	89	737	97	752	99	822	97
Moldavia	360	96	490	88	500	86	600	95	730	89	810	91	910	73	1000	96
Tadjikestan	320	94	370	82	380	95	420	93	450	79	520	91	550	89	550	71
Armenian	721	70	720	73	750	80	720	70	911	95	911	99	920	99	920	99
Total	3290	86	3684	85	3800	81	4202	86	3695	84	5006	85	5537	86	5822	91

TA - total area protected (thousands of ha)
EC - efficiency coefficient (%)

tion of crystallizing reagents in the later stages of hail formation is practically useless.

It was found that a wide range of hailstorms may occur depending on the thermodynamic state of the atmosphere and wind regime, these hailstorms having substantially different structure and dynamics. Much like Marwitz (1972) and Browning and Foote (1976), we recognize three main types of hailstorms: single cell, multicell and supercell ones.

Experimental studies showed that one should differentiate modification techniques depending on the type of a hailstorm, dividing them into those aimed at suppression the fall of hail from the hail-forming cells and those preventing the formation of hail in the newly developing convective cells.

In case of single cell hailstorms, modification aimed at suppression the fall of hail is practically useless, since individual cells are typically axi-symmetric and not mobile, and they have a single-stage process of hail formation. Precipitation from these clouds suppresses updrafts, thus causing a convective cell to decay. In this case, it is necessary to carry out modification so as to prevent primarily the formation of hail in the newly developing cells. Those cells are seeded which occur at a level of the $-6^{o}C$ + $-8^{o}C$ isotherms and over, seeding beging conducted just after the apperance of their first radar echo. The period of hail formation from this moment on is short and in some cases does not exceed 5 minutes. Seeding in proper time is therefore required for the most effective modification with a minimum consumption of seeding agent. Schematic diagram showing single cell cloud seeding is given in Fig. 1.

Cell elements of a multicell hailstorm have the structure and behavior similar to those of a single cell, but they exhibit a considerable assymetry and tilt. Due to this, descending precipitation suppresses updrafts only partially, resulting in longer lifetimes of individual convective cells and providing a hailstreak which is nearly continuous. A characteristic feature of multicell hailstorm modification aimed at preventing the propogation of hail formation process is the necessity to suppress the newly formed convective cells and the formation of hail in the mature convective cells.

The greatest effect for this type of modification can be achieved by preliminary seeding of the near-cloud space ahead and in the direction of hail formation process propagation in the weak-echo region beneath the overhang of radar echo. Schematic diagram showing multicell hailstorm seeding in case of prevention of hail formation process propagation is given in Figure 2.

Modification of multicell hailstorm (which has not reached the mature stage of evolution) aimed at preventing hail formation is conducted much in the same manner as in the case of a single cell storm. Schematic diagram showing multicell hailstorm seeding to prevent hail formation is given in Figure 3.

Supercell clouds have a unicelluar structure which is circular or elliptical with a characteristic horizontal dimension of 20 to 30 km and a vertical extent of 12 to 15 km. These clouds have an extensive zone (5 to 12 km) of strong organized updraft (25 to 40 m s^{-1}) on the right forward flank in the frontal part. The updraft zone is revealed as a weak-echo region bounded by a strong echo vault from above, the lower portion of overhanging echo in the frontal and right-flank part, and high-refectivity gradients on the opposite side. A supercell cloud has a lifetime of one to several hours and is accompanied by severe damaging hail in a streak 10 to 15 km wide and several tens of kilometers long. Supercell hailstorms form in a highly unstable atmosphere with a moderate to strong wind shear.

Supercell hailstorm evolution begins with the initiation of organized updraft zone which can be recognized by the appearance of radar echo hook, overhang and its lower portion on the right flank. Because of this, it is necessary to begin supercell hailstorm modification aimed at preventing hail formation as soon as these indications are observed. This preventative modification is conducted in much the same manner as modification of an isolated developing cell in a multicell hailstorm, i.e. the entire area in the upper part of the high reflectivity region is seeded at a level of $-8^{o}C$ + $-12^{o}C$ isotherms and 1 km higher if it extends to higher altitudes, as well as the entire regions of weak echo, overhang and its lower right-flank portion at the $-2^{o}C$ + $-6^{o}C$ level. Due to this, the hail growth zone located above the updraft in the lower right-flank portion of overhanging echo, which in turn will result in the disturbance of continuous self-maintained and self-gnerated supercell process and consequently, in its decay. So far, these works have been experimental by their nature. However, the results of the modification operations carried out in the North Caucasus (Pomtel'nikov V.A., Shtul'man N.G.) showed that in principle, supercell hailstorm suppression is possible.

Soviet scientists continue to test the method of hail suppression suggested at the Transcaucasian Hydrometeorological Research Institute (Lominadze P. N. et al.) in Georgia. Hygroscopic reagents (NaCl) are injected into the warm part of a cloud and simultaneously or just after that, crystallizing reagents (AgI) are introduced into its supercooled part. Large droplets begin to form rapidly on salt particles due to condensation in the warm part of the cloud, this process being followed by their conversion to precipitation-size particles by coagulation with smaller droplets. Falling from the cloud, precipitation particles reduce its liquid water content. At the same time, some large droplets may be carried to the upper part of the cloud where they may freeze and increase the number of hailstone embryos acting as competing embryos. Crystallizing particles introduced simultaneously into the supercooled part of the cloud act as main competitors for natural hailstone embryos.

This method used since 1967 gives good results for the treated regions. It should be noted that the experiments carried out during the period 1978 to 1979 showed sufficiently high effectiveness of hailstorm modification even in those cases where only hygroscopic reagent was used for seeding. This method appears to deserve further study.

In the hail suppression systems in the Soviet Union and some other countries hailstorm modification is conducted by means of ground-based artillery and rockets.

On the average, each anti-hail detachment has 25 to 60 operational days during a season and treats 50 hailstorms or more, consuming 18 to 30 artillery shells and 3 to 6 rockets per storm, this number sometimes amounting to hundreds of shells and dozens of rockets depending on the type of hailstorms.

The Soviet reagent delivery system adequately complies with the main requirement of modification method - to provide for the precise and expeditious delivery of aerosol into the supercooled part of a cloud at any time and practically in any weather situation.

It is our opinion that the aircraft used for cloud seeding with crystallizing reagent aerosols do not adequately comply with the requirements imposed. This is primarily due to the fact that seeding aircraft might not provide for the expeditious delivery of appropriate amounts of reagent directly into the area of hail initiation and growth in a cloud because of stringent flight and maneuver limitations when flying at the cloud base level in stormy weather (especially, in mountainous regions). It appears that the use of high-altitude aircraft for this purpose will be severely complicated by high flight speeds and limited precision of reagent injection from high altitudes to the $-5^{\circ}C$ + $-10^{\circ}C$ levels.

Analysis of the results of hail suppression activities suggests that a better insight into hail physics is essential to increase the effectiveness of hail protection. Therefore, there is an urgent need to develop a theoretical model of hail cloud in real space and time.

The most complete numerical model of hail cloud in the USSR with the best operation performance is that developed by Prof. Kachurin L. G. and his associates. It is a two-dimensional non-steady state model taking into account both thermodynamical and microphysical processes which lead to hail formation, growth and fall from a cloud. Using this model, the first experiments were carried out to compare the results of calculations and observations of radar reflectivity and kinetic energy of a hailstone flux (Kartsivadze A. I.). This model enables one to analyze actual hailstorms, both naturally developing and modified with crystallizing regents. The results of numerical analysis showed that the competing embryo concept (i.e., competition between natural and artificial crystals) which forms the basis of the method of hail cloud modification is well-founded from the physical point of view; in principle, hail formation suppression by introducing crystallizing reagents into the supercooled part of a cloud is possible; and the effectiveness of modification is an extreme function of both the concentration of artificial ice nuclei and the level of their injection.

At the present time, the results of studies and experiments on the physics of convective clouds and experience gained in the hail suppression activities in the USSR have been summarized and will be published in the form of Hail Suppression Management and Procedure Manual. It will present physical fundamentals of modification of clouds with various structures, radar methods of hail detection, procedure of making specialized weather forecasts, and estimates of the economic effectiveneness of hail suppression activities.

Analysis of the state of the art of hail suppression works in the Soviet Union and other countries shows that further increase in the effectiveness of hail suppression operations involves thorough and comprehensive studies of hail phsyics and the methods of hailstorm suppression.

As many countries have shown great interest in the development and improvement of hail suppression methods, it seems timely to consider the possibility of setting up an international research project on hail suppression engaging all interested states.

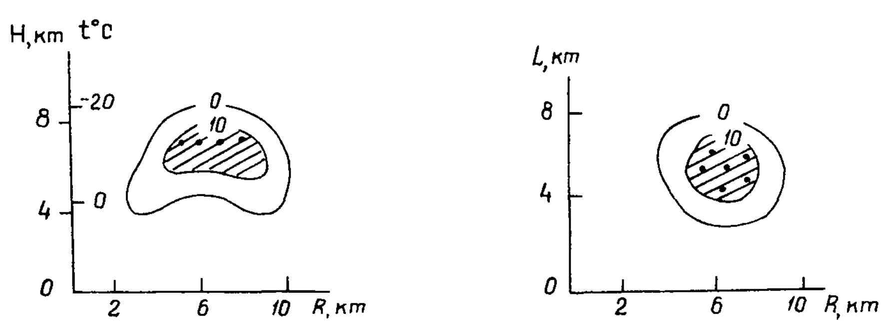

Figure 1. Schematic diagram of single cell cloud seeding in the experiments on hail formation suppression. Reagent was injected at position of dots.

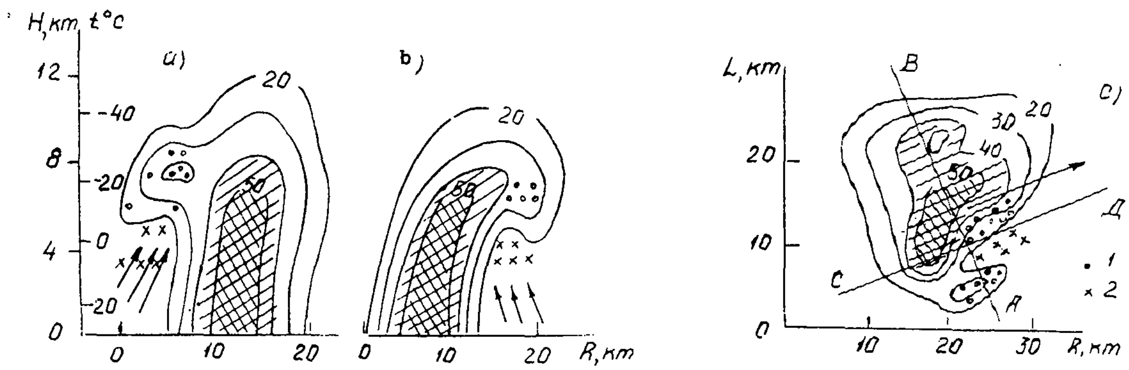

Figure 2. Schematic diagram of multicell hailstorm seeding in the experiments on prevention of hail formation process propagation:

a) - vertical section along the line AB (in Fig. 2c) through the weak-echo region in the plane normal to the direction of cell motion;
b) - vertical section along the line CD (in Fig. 2c) through the maximum radar echo and the weak-echo region in the plane parallel to the direction of cell motion;
c) - horizontal section at an altitude of about 6 km;
1,2 - location of reagent injection into the region of hail formation and initiation, and into the updraft zone, respectively.

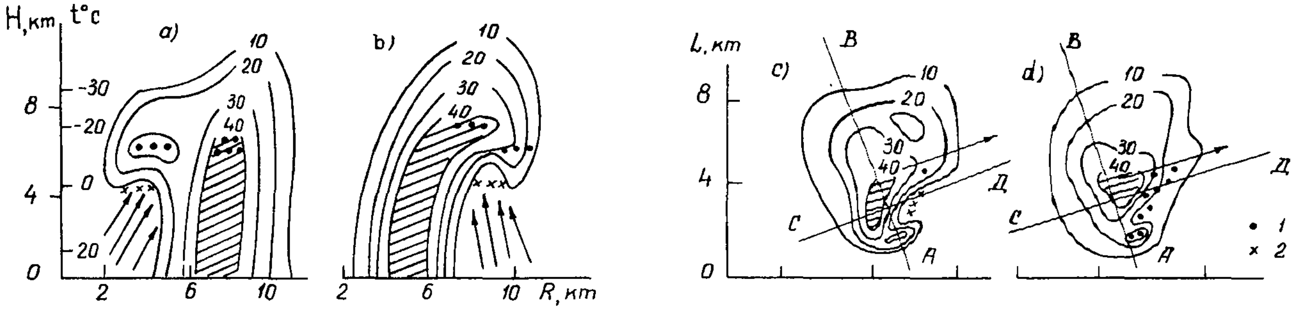

Figure 3. Schematic diagram of multicell hailstorm seeding in the experiments on hail formation prevention:

a) - vertical section along the line AB (in Fig. 3c) through the weak-echo region in the plane normal to the direction of cell motion;
b) - vertical section along the line CD (in Fig. 3c) through the weak-echo region in the plane of main cell motion;
c) - horizontal section at a level of the $-2^{0}C$ + $-12^{0}C$ isotherms;
d) - horizontal section at a level of the $-10^{0}C$ = $-12^{0}C$ isotherms.