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SURVEY OF WEATHER MODIFICATION
IN THE SOVIET UNION: 1973

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ABSTRACT

On the basis of a review of abstracts of articles published mostly since 1969, a summary has been prepared of Soviet research in weather modification. Hail suppression and precipitation stimulation still are major areas of activity in the USSR, but in recent years they have begun to do research on lightning suppression and the use of heat for the dissipation of warm fog in stratus. The articles surveyed show little evidence that Soviet scientists, unlike their American counterparts, are convinced of the value of randomized experiments in the evaluation of cloud seeding hypotheses and there is no evidence in this literature that Soviet scientists have been tackling the modification of large scale weather phenomena.

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This report is another in a series of surveys of weather modification research in the Soviet Union carried out by the author. This review is based mostly on abstracts of the papers listed at the end of the report. Unfortunately, few of the papers have been translated, and abstracts give few details. A reader who wants to know more about any particular subject will have to consult the original papers.

Research on weather modification, in progress at various institutes of the hydrometeorological services of the USSR, have been reported by several authors. Gaivoronskii and Solov'yev (1971) reviewed studies made since 1948 in the Division of Artificial Modification at the Central Aerological Observatory. Investigations covered a wide spectrum of topics: the ice forming properties of silver iodide and lead iodide; the clearing of supercooled clouds and fogs by means of ice-nuclei seeding from the ground and from an aircraft; activities over the last ten years in the study of hail processes and hail modification in Transcaucasia, Moldavia and Crimea. Anti-hail programs were started in Moldavia in 1964 and in the Crimea in 1968. By 1970, the area being "protected" in these districts was 340,000 hectares.

Scientists in the Central Aerological Observatory are working on a dynamic method for modifying convective clouds by means of seeding with insoluble pulverized reagents. They also are studying the possibility of reducing lightning activity from thunderstorms

by initiating an artificial corona discharge. It is not clear if this involves the technique being tested by NOAA scientists which involves the seeding of clouds with a very large number of metallic needles.

There continues to be an active program in cloud physics and cloud modification research at the Ukranian Hydrometeorological Research Institute located in Kiev. Bakhanova and Polovina (1970) edited a collection of articles dealing with a wide variety of subjects mostly associated with the seeding of stratiform clouds but also including some work on the modification of convective clouds. Polovina (1971) published a book entitled Modification of Stratiform Air Mass Clouds dealing with the following subjects: characteristics of air mass clouds during the cold season; experimental investigations of the crystallization process in cloud scattering; estimates of the possible quantity of artificial precipitation from air mass clouds; the dissipation of air mass clouds and fogs.

Aleksandrov and Litvinov (1971) wrote a short paper summarizing the studies of artificial modification of clouds and precipitation carried out at the Institute of Experimental Meteorology at Obninsk. The principal efforts were concerned with the following studies: evaluation of the water resources of clouds suitable for modification in the central parts of the European USSR; the redistribution of precipitation; and the dissipation of supercooled stratiform and cumulus clouds.

Stepanov (1971) described a one-week conference on the subject of cloud physics and artificial modification held in Obninsk entitled The First All-Union School of Young Scientists Concerned with Cloud Physics. It was sponsored by the Main Administration of the Hydrometeorological Service and its purpose was to acquaint young scientists with the problems of cloud physics and weather modification. Specialists from the High Mountain Geophysical Institute discussed the physics of hail growth and the use of seeding techniques for modifying hail. I. P. Polovina from the Ukrainian Scientific Research Hydrometeorological Institute discussed experimental investigations for modifying supercooled clouds. N. I. Vul'fson and Levin of the Institute of Applied Geophysics discussed the use of jets for modifying meteorological phenomena, and A. D. Solov'yev of the Main Geophysical Observatory discussed theoretical principles for modifying warm fog.

Buikov and Muchnik (1971) edited a Transactions of the Ukrainian Scientific Research Hydrometeorological Institute devoted to the subject of cloud physics and weather modification. Its title is "Artificial Modification and Radar Investigations". The papers range from discussions of field experiments on clouds to laboratory experiments on the structure of water absorbed on phloroglucinol. Burtsev (1972) edited a Transactions of the High-Altitude Geophysical Institute entitled "Artificial Modification of Hail Processes".

1. Nucleation

Soviet scientists continue to investigate the efficiency of various types of ice nucleating substances. Gromova and Lenshin (1971) completed a study of the quantity of Dry Ice needed for precipitation inducement from cumulus clouds in terms of the degree of supercooling and the thickness of the supercooled part of the cloud. As expected, they concluded that the more the supercooling, the smaller the amount of carbon dioxide required. They reported that the minimum thickness of a supercooled convective cloud from which artificial precipitation could be induced is 1.5 km. The same article gives a comparison of the nucleating abilities of various other substances as applied to the augmentation of precipitation. They considered the following substances: lead iodide, copper sulfide, sodium chloride with cement and carbon dioxide.

Stalevich and Uchevatkina (1971a, b) examined the quantity of silver iodide, lead iodide, or copper sulfide needed for precipitation initiation in terms of cloud thickness, liquid-water content and the temperature of the cloud at the seeding level. In the first of their two articles, they studied the importance of the liquid-water content of a cloud in terms of the efficacy of ice-nuclei seeding. They used a theoretical model and calculated the rate of growth of precipitation in a seeded cloud as a function of the cloud thickness and liquid water. It was found that on the average, precipitation should occur 14 to 17 minutes after seeding

and that the time required should decrease as the liquid-water content increased.

In their second article, Stalevich and Uchevatkina (1971b) presented nomagrams which make it possible to determine the quantity of seeding reagent needed for most effective rainfall augmentation in terms of cloud thickness, liquid-water content and temperature. They claimed that their calculations are supported by experimental data and recommend that their nomagrams be used in practical seeding operations.

Various other authors have published analyses dealing with ice crystal nucleants. Nikandrov (1970) examined the conditions under which dispersed particles of various substances are capable of stimulating the formation of ice particles at sub-freezing temperatures. He concluded that the ice-forming activity of a particular reagent is determined primarily by the extent to which it is capable of establishing hydrogen bonds between the H_2O molecules in the primary condensate layer. Zadumkin and Khokonov (1970) conducted experimental studies of ice crystals and the factors governing their growth.

Bromberg et al. (1969) and Bychkov, Gromova and Sumin (1971) investigated the ice-forming properties of powdered copper sulfide under laboratory and natural conditions. They reported that the reagent is characterized by a temperature threshold of $-3^{\circ}C$ and yields 1.2×10^{12} ice crystals per gram of copper sulfide at a temperature

of -10°C . Experiments were performed in which the CuS was introduced into convective clouds by means of rockets and explosive shells containing as much as 2.5 kg of reagent. It was claimed that CuS injected into convective clouds led to the formation of precipitation when temperatures of the cloud boundary were -6°C or less and the cloud thickness exceeded 2.5 km. Stratiform clouds were crystallized when the temperatures at the top were -7°C or less and the cloud was seeded with 400 or more grams of CuS per kilometer of aircraft flight.

Malkina and Patrikeyev (1971) proposed a procedure for the rapid testing of the nucleating properties of any substance. It consists of introducing a known weight of the substance into a standard cold chamber containing a supercooled fog through which a light beam passes from a standard light source to a photo detector. The increase of transparency through the artificially produced and seeded fog is compared with the results when an equal weight of silver iodide is introduced into the chamber with all other factors unchanged.

Burtseva, Burtsev and Begun (1970) and Batonin et al. discussed an extension of work which has been in progress for quite a few years under the direction of scientists at the High Altitude Geophysical Institute. It consists of a scheme for measuring the dispersion and washout of silver iodide particles which are put into the atmosphere or hail clouds by means of artillery shells. They

employed radioactive potassium-32 and non-radioactive silver iodide (75 grams) in an "El'brus-2" anti-hail shell. It was reported that 30 seconds after the explosion of the shell, they measured the following items: the mean silver concentration in the dispersed field amounted to $5 \text{ to } 6 \times 10^{-7}$ grams liter⁻¹; the space charge reached 3×10^{-13} Coulombs cm⁻³; the radius of the tracer particles was 0.1 to 0.2 of a micron; and the average diameter of the aerosol cloud was 50 m and was expanding at a rate of about 3 m sec⁻¹. The mean background silver concentration in the atmosphere was found to be 2.1×10^{-12} grams liter⁻¹. Concentrations increased in the presence of inversion layers. The mean value of the natural radioactivity during the observational period was $2 \text{ to } 5 \times 10^{-19}$ Curies liter⁻¹ while the space charge in the free atmosphere at altitudes of 3 to 4 km was positive and equal to 1×10^{-17} Coulombs cm⁻³. The aerosol measurements were made by means of an IL-14 airplane using an instrument called the "Opora" having a highly effective "NEL-IV filter".

2. The Spread of Crystallization in Seeded Clouds

Soviet scientists, particularly those from the Central Aerological Observatory and from the Ukrainian Scientific Research Hydrometeorological Institute, have given a great deal of attention to the rate of spread of the crystallization zone following ice nuclei seeding.

Apparently, Dry Ice was used as the seeding agent in almost all the experiments. Buikov and Polovina (1969) and Polovina (1970a) have reported the results of 104 experiments in which the dimensions of the ice crystal zones in seeded stratiform clouds and the rates of expansion of the zones were related to the properties of the cloud and wind velocity. They reported that the rates of expansion of the crystallization zones and their dimensions are not dependent on wind velocity. The rates of expansion were found to depend on the properties of the cloud layer and on the intensity and nature of the mechanisms governing the development or destruction of the clouds, i.e., mostly the field of vertical motion.

Buikov and Polovina (1969) and Polovina (1970a) cited three types of expansion of the crystallization zone: the rate of expansion increases with time; the rate of expansion is constant with time; and the rate of expansion increases initially and then decreases with time. These three types of expansion are said to be related to the natural mechanisms in the atmosphere leading towards the destruction, stabilization or intensification of the cloud. It was found that in the first type of expansion, the crystallization front propagates at 0.7 m sec^{-1} during the initial period of 1.1 m sec^{-1} at the end of the period of zone expansion.

The same problem has been discussed by Levin, Polovina and Tkachenko (1970) and Krasnovskaya, Levin and Tkachenko (1971) and Gaivoronskii et al. (1970). The first two papers discuss four types

of expansion of the crystallization zone in stratiform clouds called Types A, A', B and C. In Type A there is accelerated expansion at the start of the process and a slowed growth rate at the end. In Type A' the growth rate accelerates throughout the period of expansion of the crystallization zone. In Type B the growth rate is constant with time and in Type C is decreased with time. In the first paper, Levin, Polovina and Tkachenko (1970) reported the results of 95 experiments carried out in the Ukraine. They related the rate of expansion of the crystallization zone to a model of horizontal turbulent diffusion which they had proposed earlier. They found the following turbulent properties were applicable in this problem: fluctuation velocity approximately $1/2 \text{ m sec}^{-1}$; the rate of dissipation of the turbulent energy approximately $10 \text{ cm}^2 \text{ sec}^{-2}$; the Langrangian length scale 10^3 m ; the Langrangian time scale about 10^3 sec .

Chotorlishvili (1971) investigated the turbulent diffusion of a reagent in a cloud in terms of the concentration of the reagent and a suitable coefficient of turbulent diffusion. He derived an expression for the concentration of a reagent in terms of distance and time from an instantaneous point source in a cumulus cloud.

Some properties of a seeded stratiform cloud have been reported by several authors from the Ukraine. Dubinchuk and Polovina (1971a) measured the sizes of ice crystals in seeded clouds. They reported that the crystals were in the form of plates, and in most cases had

diameters of 40 to 80 microns with the largest ones attaining sizes of 150 microns. During natural crystallization, it was most common to observe dendritic crystals whose sizes were greater than the crystals in the seeded clouds. Dubinchuk and Polovina (1971b) measured the temperatures in seeded clouds and reported them to be 0.3 to 0.5°C warmer than they had been before the crystallization. Voyt et al. (1970) also reported measurements of temperature increases of 1/2°C following the artificial crystallization of supercooled clouds. Dubinchuk and Polovina (1971b) reported that for 40 to 50 minutes after modification, the temperatures in the crystallization zone remained virtually unchanged. This led them to conclude that the heat exchange with the surrounding medium proceeds very slowly.

Voyt et al. (1970) also measured the ice-crystal concentration following seeding. During the first 15 to 20 minutes the concentration on the boundaries and in the interior of the crystallization zone were about the same order of magnitude being 15 to 30 crystals per cubic centimeter. During this period the boundaries of the ice-crystal zone were distinct, but as time went on and the zone expanded, they became less distinct. At the center of the zone, the crystal concentration remained at about 15 to 30 cm⁻³ but decreased considerably toward boundaries.

Dubinchuk, Leskov and Polovina (1970) used two airplanes to study the change of a region of crystallization in the vicinity of mountains. The seeding was carried out in clouds along a line

perpendicular to the wind direction. As the crystallization zone approached the mountains, its rate of approach decreased. This result was explained in terms of the deformation of the wind flow as the air approached the mountains.

Leskov (1971c) discussed experiments from which estimates were made of the maximum time required for the total crystallization of supercooled clouds and fogs seeded with ice nuclei. The study was based on one experiment employing seeding of fogs from the ground and 14 experiments involving the seeding of stratiform clouds from aircraft. The time required for the total disappearance of the water droplets in the seeded clouds did not exceed 125 to 200 seconds. The author concluded that the ice crystals formed as a result of the rapid sublimation growth on nuclei rather than as a result of droplet freezing.

Dubinchuk, Polovina and Tkachenko (1970) examined the reformation of supercooled clouds following their dissipation as a result of ice-nuclei seeding. They considered the processes of vertical motion of the air, vertical turbulent exchange, radiation and heat flux, particularly how they effect liquid-water content in the cloud layer. It was concluded that the cloud would or would not reform depending on whether the vertical air motion was upwards or downwards respectively. Such results occurred in twelve out of sixteen experiments.

3. The Modification of Warm Fog in Clouds

Solov'ev (1969) examined the use of heat and hygroscopic nuclei for the purpose of dissipating warm fog. Simonov and Nikandrova (1971) made calculations of the energy required for dissipating fog as a function of the meteorological conditions, length of the heated strip, the distribution of heaters, etc. They derived equations for making the calculations for any set of conditions.

Scientists at the Ukrainian Scientific Research Hydrometeorological Institute have been studying the use of films of fatty alcohol for preventing the formation of evaporation fogs. They have a scheme for emulsifying a mixture of water and alcohol in order to facilitate the spread of the alcohol over the water. Bakhanova and Solunek (1970) described how this is accomplished by means of high frequency sound waves. They reported that the mean size of the alcohol droplets is about 0.1 of a micron and that the mixture of water and alcohol readily produces a thin film when it is sprayed on a water surface. Bakhanova, Solunek and Terziyev (1971) described field tests in which the suspension of alcohol in water was used for modifying evaporation fogs over the Kola Gulf. Five experiments were performed and films were successfully produced over relatively small areas. The authors noted that it is difficult to get a film over a large area and to maintain it. This is a fact well known to scientists who have used fatty alcohol films to suppress evaporation over large lakes.

Terziyev (1970) who is the chief of the Murmansk Administration of the Hydrometeorological Service has been particularly interested in the work on the suppression of steam clouds in the Kola Gulf. He noted that his administration makes predictions of the occurrence of steam fogs based on meteorological information and water temperatures and then performs experiments on the use of a fatty alcohol film. He claimed that this technique has made it possible to stop steam fogs over an area of several square kilometers.

Fedoseyev (1970) reviewed work of various investigators on the use of hygroscopic substances for modifying warm clouds. He focused his attention particularly on the efficacy of these techniques for the dissipation of clouds and the production of precipitation. At the Institute of Experimental Meteorology at Obninsk, experiments were conducted by Aleksandrov and Yasevich (1971) on the effects of condensation nuclei on the characteristics of fog formed during adiabatic expansion of air in a chamber having a volume of 3,200 cubic meters. Condensation nuclei were produced by vaporizing ammonium chloride in a special generator. The quantities of additional nuclei introduced into the fogs ranged from 0.01 to 1.0 mg m⁻³. When the quantity of nuclei exceeded 0.1 mg m⁻³, the nuclei exerted a substantial effect on the concentration and mean size of the droplets in the fogs and on the attenuation of light caused by the fog. When the quantity of nuclei added amounted to 0.01 - 0.1 mg m⁻³ there was an appreciable increase in the stability of the fog and in its lifetime.

Shvarts (1972) made theoretical studies of the effects of electrical forces in the coagulation of liquid particles. He considered the case of water droplets having a radius of 10 microns and charged to their maximum capacity which were ejected into monodispersed clouds containing uncharged water droplets having radii of 5 to 7 microns. These clouds were taken to have liquid-water contents between 0.3 and 2.0 g m⁻³. It was suggested that electrical inhomogeneities in clouds can affect the coagulation process.

4. Precipitation Modification

Litvinov (1971) summarized his views on the efficacy of cloud seeding for increasing precipitation. On the basis of aircraft sounding data collected over European USSR, he estimated the frequency of occasions when clouds suitable for seeding would be present and calculated the quantities of additional precipitation which might be made to fall. Litvinov indicated that over very large areas, additional precipitation amounting to 10 to 40 per cent above the normal winter level could be achieved by means of cloud seeding. He further estimated that by increasing the fall of snow over the watershed of the Volga River, it would be possible to increase the annual runoff by 4 per cent. He also suggested that by redistributing precipitation one could reduce the fall over an area by 10 per cent. Litvinov's earlier experimental work showing the occurrence of a "rain shadow" downwind from the seeding area was severely criticized by Leonov (1971). Litvinov indicated that he could not make a quantitative estimate of the quantity of additional rainfall

which could be induced from convective clouds, but he did say that the amount of additional precipitation from warm stratiform clouds in summer would amount to about 3 per cent of the normal summer precipitation.

Scientists from the Ukrainian Scientific Research Hydrometeorological Institute have had active programs of research in the modification of precipitation from various cloud systems and have focused considerable interest on frontal clouds. A series of articles is concerned with the question of how much additional precipitation can be made to fall from clouds which would not have precipitated naturally. Presumably Dry Ice was used to seed super-cooled clouds in the Ukraine.

Mogila and Polovina (1970a) made use of aircraft soundings over the Ukraine to study the properties of cloud layers in the vicinity of fronts. They were particularly interested in the height and thickness of cloud layers. In a second paper Mogila and Polovina (1970b) estimates that in about 50 per cent of the frontal situations over the Ukraine, the conditions were favorable for inducing precipitation from clouds which were not yielding precipitation naturally. Favorable conditions occurred most frequently during February and March. Leskov, Mogila and Polovina (1971) calculated that winter-season precipitation from frontal clouds not yielding natural precipitation could be increased by three to five per cent.

In a third paper, Mogila and Polovina (1971) used aircraft soundings for the years 1951 to 1963 to study the characteristics of altocumulus and altostratus clouds and evaluated their suitability for artificial modification. They concluded that during the cold season of the year, altocumulus and altostratus are suitable for seeding in 85 and 65 per cent of the cases respectively.

The papers just cited and others which have appeared in the Soviet literature, indicate that Soviet scientists have been attempting on a systematic basis, to estimate the frequency of seedable clouds. This has been done by means of aircraft sounding data, radiosonde data and observations made from the surface. Admittedly this type of exercise involves many uncertainties, but nevertheless, it supplies a basis for estimating the economic feasibility of cloud seeding operations. Also it is of value in determining where cloud seeding experimentation should be carried out.

Leskov (1970) described that he referred to as a "new method" for discriminating zones of increased precipitation from seeded frontal clouds. It takes into account the time of fall of precipitation particles and the wind regime in and under the clouds. The shape and size of the area of expected increased precipitation are determined by the mean wind in the seeded layer. Leskov indicated that the procedure of evaluating seeding experiments during the period 1960 to 1966 was inadequate because of the technique for specifying the area of expected precipitation increase was not

sufficiently precise. He concluded that more than half of the experiments can not be evaluated because the precipitation fell outside the measurement area. He concluded that the generalizations on the efficacy of cloud seeding based on the analysis following earlier methods must be regarded as unsound. Leskov (1971a) analyzed the effects of seeding frontal clouds and concluded that there was an increase of precipitation which increased with displacement from the modification line up to a distance corresponding to a 2 to 4 hour transfer by the wind. He concluded that there was no data which indicated the presence of a precipitation shadow. The same conclusion was reached earlier by Leskov and Polovina (1969). The intensity of artificial precipitation over this distance amounted to about $0.30 \text{ mm hour}^{-1}$. Akimov and Leskov (1971) also compared two methods of defining the area over which artificial precipitation would be expected to fall following seeding of frontal clouds. They expressed doubt concerning the correctness of results of studies reported earlier asserting that ice-nuclei seeding of frontal clouds leads to the appearance of zones of a decreased precipitation situated beyond the zones where precipitation was increased.

Leskov and Nerobeyeva (1971) analyzed vertical soundings through frontal clouds made in the experimental meteorological polygon in the Ukraine during the period 1960 to 1970. They concluded that clouds yielding natural precipitation are suitable for seeding during a time interval representing 42 per cent of their

total duration over the experimental polygon. They asserted that the so-called "coefficient of suitability" of seeding decreases linearly with an increase in the intensity of natural precipitation.

The question of the factors which characterize the seedability of frontal cloud layers was examined by Akimov, Leskov and Nerobeyeva (1971) who examined 111 vertical soundings of frontal clouds made over the Ukraine during the period 1960 to 1970. The authors related seedability to vertical cloud thickness, height of the cloud above the ground, temperature and wind regimes, the mean liquid-water content and moisture reserve.

Polovina (1970b), on the basis of 40 experiments in modifying air mass stratiform clouds, established criteria for the seedability of clouds for the purpose of increasing precipitation. Cloud layers were considered suitable for seeding if they had the following characteristics: the integrated liquid water measured vertically through a cloud amounts to 30 g m^{-2} ; the cloud persists for more than three hours; and the cloud has a temperature not above -2°C . It was reported that the lifetime of clouds suitable for seeding did not exceed 12 hours in 50 per cent of the cases and were less than 24 hours in 75 to 80 per cent of the cases. It was estimated that the quantity of precipitation which could be produced artificially from air mass clouds during the cold season of the year over an area of about $1,000 \text{ km}^2$ would amount to 16 to 30 mm in the western and southern parts of the Ukraine and 35 to 55 mm in the northern

and eastern parts. In the region of the experimental meteorological polygon, the possible quantity of additional precipitation during the winter season varied in the range 17 to 42 mm. The mean value is 26.6 mm which amounts to 20 per cent of the normal precipitation during the cold season of the year.

On the basis of data from 19 experiments involving the modification of frontal clouds, Leskov (1971b) compared the observed increase in precipitation with the liquid-water content of the seeded clouds. The ratio of these two quantities is called the "coefficient of realization of water reserves". In most cases, this quantity exceeded unity with a maximum value being 46. In experiments with clouds usually not yielding precipitation naturally, the value of the coefficient was less than unity. With an increase in the intensity of natural precipitation the coefficient increases. It was concluded that the formation of artificial precipitation following seeding is determined by the same factors which determine the formation of natural precipitation.

Stalevich and Uchevatkina (1971a) of the Main Geophysical Observatory made calculations of the formation of precipitation in convective clouds 3 km thick having different liquid water content profiles. It was concluded that precipitation should appear about 17 min following the seeding and that the precipitation would appear earlier as the liquid-water content is increased. Calculations were also made of the width of the zone of artificial precipitation and the amount of precipitation in different parts of

the clouds. The authors determined the seeding rate at which 90 to 95 per cent of the liquid water would fall as precipitation. (This information has come from an abstract of a paper and hence it is not possible at this point to make a realistic evaluation of the validity of the calculations and conclusions offered by Stalevich and Uchevatkina. It would appear, however, that they have oversimplified the problem.)

Zakharov (1972) described experiments with convective clouds in 1968 during the wet season in Camaguey and Oriente Provinces in Cuba. They reported that seeding with hygroscopic reagents such as NaCl produced no modification effects. On the other hand, they concluded that Dry Ice was very effective in increasing precipitation. Over the test area in Camaguey Province there was 25 per cent more rain than the maximum quantity observed over a 10-year period. It was claimed that the likelihood of this occurring by chance was less than 1 in 500.

In Oriente Province the rainfall was 16 to 25 per cent greater than normal over the target area whereas over the control area it was 24 to 30 per cent below normal. The author reported that "warm" clouds developed following the seeding with CO₂.

Mkhitaryan (1969) discussed a study of the factors controlling the water level of Lake Sevan. The water is crucial to the economy of Armenia because it is used for irrigation, and because as it flows into the Razdan River, it produced hydroelectric power. Over

the past three years the level of Lake Sevan has dropped considerably and a study of the meteorological situation led to the institution of cloud seeding operations over the watershed with the goal of increasing the lake level according to a report by Yerevan Radio on July 4, 1972.

The value of artificial precipitation in agriculture was studied by scientists from the Ukraine Scientific Research Hydro-meteorological Institute (Unknown, 1970). A formula was developed relating agricultural yield to precipitation. Presumably the crops were grains, but that is not definite at this point. It was concluded that the redistribution of precipitation over a small area over which precipitation does not vary a great deal would have little effect on the harvest. On the other hand, the artificial redistribution of precipitation over more arid regions would lead to an increase in agricultural yields.

Scientists at the Main Geophysical Observatory have been experimenting with the use of cloud seeding for the purpose of increasing rainfall over forest fires in an effort to extinguish them. Sumin (1971) discussed 20 experiments during 1968 and 1969 which were conducted over the areas of Krasnoyarskaia, Tyumenskaia and Irkutskaia Oblasts. It was reported that in six cases it was possible, by means of the artificially induced precipitation to extinguish fires over a total area of about 12,000 hectares. According to Sumin, in other experiments the fires were localized

when the seeding led to precipitation either directly on the fire or in its immediate neighborhood. He emphasized that the method is most effective when dealing with large forest fires persisting over long periods of time, i.e., over several natural synoptic periods. Sumin pointed out that since this technique depends on weather conditions, it can not always be used, and therefore it can not replace other methods of fighting forest fires.

In a subsequent paper, D'yachenko, Sumin and Shishkin (1972) gave additional information about the technique of extinguishing forest fires by means of cloud seeding. They pointed out that the method is applicable only when well developed convective clouds exist over the region of the fire. They recommended the use of radar-equipped, high speed aircraft such as the AN-24, TU-124 and TU-134 outfitted with magazines for firing pyrotechnical seeding devices. The authors stated that when cloud seeding is used in combination with conventional procedures, there can be effective forest-fire fighting especially when the fire covers an area greater than 200 hectares. They reported that the cost of fighting forest fires by conventional ground methods in remote and inaccessible regions of Siberia averaged thirteen rubles per hectare while the corresponding cost for fighting forest fires by means of the seeding method used in 1968 amounted to two rubles per hectare. Over their experimental areas they encountered favorable seeding conditions on about 50 per cent of the days with fires.

5. Modification of Convective Clouds

A number of Soviet scientists are investigating various techniques for destroying convective clouds. At the Institute of Applied Geophysics, Vul'fson, Levin and Cherenkova (1970a, b) have been studying various techniques for inducing downdrafts in cumulus clouds for the purpose of dissipating them. They reported the results of 98 experiments. It was reported that in about 80 per cent of the cases, cloud dissipation was brought about by the initiation of descending air currents. In some cases the downdraft was initiated by the introduction, from an airplane, over a period of less than one second, of several tens of kilograms of finely dispersed cement or talc into the upper part of the cumulus clouds. The most effective method for initiating a downdraft involved the use of a jet aircraft which flew through the upper part of the cloud at a very large elevation angle. The principle here apparently is that the air from the jet engines is blown downward to start the downdraft.

Gaivoronskii, Zatsepina, et al. (1969, 1972) at the Central Aerological Observatory also discussed a method for the dissipation of cumulus by seeding them with insoluble pulverized reagents. From laboratory experiments, Vereshago et al. (1969) concluded that Kurtz bentonite powder is more effective than cement in dissipating clouds.

Vul'fson et al. (1972) presented the results of theoretical and experimental studies at the Institute of Applied Geophysics which are aimed at causing the development or dissipation of convective clouds by the initiation of ascending or descending air currents respectively. They produced updrafts by means of surplus RD-30

aircraft engines mounted on the ground. It was reported that under favorable atmospheric conditions it was possible to produce well developed cumulus clouds and in some cases cumulonimbus clouds as well. As noted earlier, they initiated downdrafts in the upper parts of cumulus by injecting insoluble particles or by flying an aircraft in almost vertical flight through the clouds.

A newspaper article (Anon, 1972) reported that students at Riga Polytechnical Institute in Latvia are designing a super-meteotron. It is stated that the system consists of six gas-turbine, aircraft engines joined in a single assembly capable of producing a current of strongly heated air reaching an altitude of 3 km. It is envisioned that such an updraft can be used to transport various chemicals, solid particles and visible substances. They proposed that the apparatus can be employed to create clouds and simulate whirlwinds and observe the behavior of rising air.

More recently, Vul'fson and Levin (1972) investigated the effects of explosives on the behavior of cumulus clouds. They used cannons to fire anti-aircraft shells into cumulus clouds 5.5 and 6.2 km thick. It was claimed that these preliminary experiments confirmed theoretical conclusions about the possibility of dissipating cumulus clouds by means of explosions.

The results of these experiments aimed at influencing cumulus cloud dissipation are difficult to accept. How was it judged that the observed cloud behavior would not have occurred even if there

had not been seeding with cement, or a flight through the cloud or the explosion of an artillery shell in the cloud?

Morachevskii, Dubrovich and Potanin (1969) made laboratory studies of the effects of surfactants on the behavior of water drops and concluded they should be considered for cloud seeding. Kokhanovich (1968) discussed tests of the effects of surfactants on the formation of precipitation in convective clouds. The aim of the experiments was to modify the surface properties of the drops and hence the coalescence and break-up processes. Surface-active agents were injected into the lower part of cumulus clouds using "anti-hail guns" having an effective range of 4 km. It was reported that if the maximum velocity of the updrafts did not exceed 15 m sec^{-1} and the gradient of the vertical velocity was about $2 \text{ m sec}^{-1} \text{ km}^{-1}$ the modification process was successful when there was an expenditure of reagent amounting to 1 to 2 g km^{-3} of cloud. It was reported that in these cases there was rain having an intensity of 0.1 to 2 mm min^{-1} . When the updraft velocity exceeded 25 to 40 m sec^{-1} , the growing droplets and surface active substances are carried to the supercooled part of the cloud where they freeze and have no effect on the growth of rain by the chain-reaction process. Several aspects of this research program are puzzling and there is cause to wonder why more has not appeared on this subject in the Soviet literature.

Gromova, Lenshin and Stalevich (1969) examined conditions for inducing precipitation from convective clouds by seeding with substances such as carbon dioxide, sodium chloride, silver iodide, lead

iodide, and copper sulfide. Gromova and Lenshin (1970) described the results of experimental investigations involving the seeding of convective clouds with silver iodide. They reported that the minimum thickness of convective clouds from which artificial precipitation can be caused to fall is 2.5 km or more depending on the degree of cloud supercooling. They further concluded, on the basis of their cloud model, that the most rapid growth of precipitation particles occurred when the maximum updraft was in the range from 9 to 12 m sec⁻¹. In such circumstances precipitation formed in times amounting to 10 to 18 min.

There has been a continuing program of research on rainfall stimulation from convective clouds at the Ukrainian Hydrometeorological Scientific Research Institute in Kiev under the direction of Kornienko (1970a, b, c, d; 1971). In the first article, the author formulated criteria which need to be satisfied in an experimental model for evaluating the effects of ice nuclei on precipitation from convective clouds. He noted that the seeding experiments should involve seeded clouds as well as not-seeded clouds and the results should be compared. The effects of modification are taken to be the differences in precipitation from the seeded sample compared to the not-seeded sample of clouds.

Kornienko (1970b) discussed the data which came from a seeding experiment in which there were 79 seeded and 92 unseeded clouds.

It was observed that 43 per cent of the seeded clouds rained while only 32 per cent of the unseeded ones rained. The greatest increase of frequency of falling precipitation following seeding occurred from clouds having a vertical thickness of about 2.5 to 3.5 km and a cloud top temperature of -6 to -12°C . In thicker clouds, the difference in the frequency of falling precipitation from seeded and unseeded clouds was insignificant because of an increase in the probability of natural precipitation. The average area of precipitation measured under the cloud base was 8.1 km^2 for seeded clouds and 5.7 km^2 for unseeded clouds. The mean duration of precipitation was 20 and 14 min respectively.

In another paper, Kornienko (1970c) presented the results of experiments in which cumulus clouds were seeded with Dry Ice. The clouds occurred over the steppe regions of the Ukraine during the period 1966 to 1968. Individual clouds were seeded and the precipitation falling from them was measured from an airplane and the amounts were compared with the precipitation falling from unseeded clouds. It was reported that on the average a seeded cloud produced from 30 to 160,700 tons of rain, while the average unseeded cloud produced from 20 to 74,000 tons of water. On the average the cloud seeding increased precipitation from an average cloud by 4,800 tons. Taking into account the mean quantity of clouds suitable for modification, it was concluded that by means of Dry Ice seeding of cumulus clouds in the experimental area, it might be possible to increase the overall precipitation by 0.4 per cent.

In still another paper, Kornienko (1970d) compared the intensity of falling precipitation from seeded and unseeded clouds. He concluded that there is a smoother time distribution in the intensity of rain from seeded clouds than from unseeded ones. The mean intensity of precipitation was 6.9 mm hr^{-1} from seeded and 3.6 mm hr^{-1} from unseeded clouds; the averages of maximum intensity were 9.5 and 5.1 mm hr^{-1} , respectively. In addition, Kornienko found a correlation between the intensity of precipitation and its duration, but in some cases, the precipitation intensity was high even though the cloud duration was very small.

Kornienko (1971) formulated a multiple regression equation for the quantity of precipitation in terms of various cloud parameters for seeded and unseeded clouds. Presumably, the cloud parameters were the ones mentioned in earlier papers, namely cloud thickness, cloud-top temperature, depth of supercooled cloud, and quantity of seeding reagent. Kornienko proposed that having two equations, one for seeded clouds and one for unseeded clouds, it would be possible to determine the change in the quantity of precipitation resulting from modification. This approach to the evaluation of cloud seeding experiments was also discussed by Buykov et al. (1972). They reported that the correlation coefficient between the computed precipitation using the multiple regression equation and the observed precipitation was 0.91. They reported that the regression equation applicable to seeded clouds was

constructed from data obtained from clouds seeded over the meteorological polygon of the Ukrainian Scientific Research Hydrometeorological Institute. This paper also gives the results of tests of the dynamical model of cumulus convection and precipitation developed by Joanne Simpson and her associates in Florida.

The results of seeding convective clouds with pyrotechnic mixtures of lead iodide and silver iodide for the purpose of augmenting precipitation from cumulus clouds has been described by Titov (1971) of the Main Geophysical Observatory. The experiments were carried out during the period 1964 to 1968 in northern Kazakhstan. It was reported that the critical cloud properties for initiating moderate and heavy precipitation are as follows: vertical cloud thickness equal to or greater than 2.5 km; thickness of supercooled parts of the cloud equal to or greater than 1.5 km; temperature at the modification level equal to or below -8°C ; concentration of reagent particles equal to or less than $7 \times 10^{11} \text{ km}^{-3}$. The author defines a "supercooling coefficient" as the ratio of the thickness of supercooled clouds to the thickness of the entire cloud and stated that when strong and prolonged showers were initiated in northern Kazakhstan the degree of supercooling of well-developed cumulus clouds was extremely great with the supercooling coefficient exceeding 0.8. It is not clear how Titov evaluated the quantity of rainfall which could be attributed to seeding as distinct from the amount that would have fallen naturally.

6. Modification of Electrical Properties of Clouds

The literature indicates that there is little research in the Soviet Union on the modification of the electrical properties of convective clouds. Sumin and Shvarts (1971) discussed the effects of silver iodide and lead iodide seeding on the potential gradient in the vicinity of convective clouds. They concluded that ordered electrification develops after the appearance of the ice phase and the formation of precipitation particles in the clouds. Gaivoronskii and Zimin (1971) reported experiments in which six thunderstorms were seeded with lead iodide by means of rockets. They concluded that there was a decrease in the frequency of lightning discharges as a result of seeding. This work was done in the Crimea, apparently in connection with a hail suppression operation.

7. Hail Suppression

Hail modification operations are still in progress in various parts of the Soviet Union. Bartishvili, Gaivoronskii et al. (1972) and Bartishvali, Benito, et al. (1972) discussed hail suppression activities being conducted by the High Mountain Geophysical Institute, The Geophysical Institute of the Georgian Academy of Sciences, the Central Aerological Observatory and the Transcaucasian Scientific Research Hydrometeorological Institute located in Tibilisi. In the first paper, there is a summary of the results of the hail modifica-

tion program conducted during the period 1966 to 1970. It includes a review of the various methods employed: the artillery method in the northern Caucasus; the rocket method in the Georgian SSR; and the method developed by the Transcaucasian Scientific Research Hydrometeorological Institute which uses artillery to introduce ice nuclei aloft and salt nuclei into the warm part of the cloud. The authors report that regular seeding of hail clouds leads to a decrease in the number of hailfalls by a factor of three or four.

Voronov, Gaivoronskii and Seregin (1969) described the procedures and results of the hail suppression projects near Korneshta, Moldavia during the period 1964 to 1968. The "Oblako" and PGI-M rockets were used to deliver ice nuclei into clouds. On the basis of crop insurance statistics, it is concluded the seeding was highly effective in reducing crop damage.

In a newspaper article, Shirokov (1971) described the results of the same hail modification program during 1971. The seeding was carried out over 100,000 hectares by means of "Oblako" rockets containing a mixture of lead iodide. Earlier silver iodide had been employed. The same "Oblako" rockets were also being used for hail modification work in the Crimea, Georgia and Bulgaria. The article also refers to an analysis of the effects of the seeding on precipitation. It is stated that over the seeded area there was an average of 10 to 15 per cent more precipitation than apparently would have been expected had there been no seeding. The article indicates that

during 1971 the Moldavian anti-hail expedition of the Central Aerological Observatory seeded over an area of agricultural crops covering 300,000 hectares. It is stated that the protected area had 23 times less damage than the control area.

Bibilashvili, Myakon'kiy and Khorguani (1971) at the High-Altitude Geophysical Institute studied the rate of freezing of supercooled droplets exposed to a cloud of ice crystals. They concluded that when the ice-crystals concentration was about 0.1 cm^{-3} only several seconds would elapse before one of them was intercepted by a supercooled droplet and cause it to freeze.

Glushkova, Lapcheva and Fedchenko (1970) discussed the techniques of seeding long-lived organized hailstorms. They concluded that with fast moving hailstorms it is necessary to begin the seeding when they are still some 3 to 10 km from the boundary of the "protected area". In the case of particularly active storms, (such as the one that occurred on 16 June 1967) the modification must proceed continuously since in such storms, hail-forming centers occur simultaneously, or at intervals of 20 to 30 min at distances intervals of 3 to 10 km.

Bibilashvili et al. (1969) summarized hail suppression activities of the High Altitude Geophysical Institute during the years 1963 to 1968 and showed how the size of the target area had reached about 1.8×10^6 hectares in 1968. A table gives effectiveness of the seeding in terms of benefit to cost ratios ranging from 26:1 to 11:1

Bibilashvili et al. (1972) discussed the hail modification programs conducted in the northern Caucasus during 1968 and 1969 and concluded that crop losses can be reduced by approximately 80 per cent. It is not clear if they used a technique of evaluating the effectiveness of hail suppression approved by the Presidium of the USSR Academy of Sciences on 8 September 1969 (Legkostup and Naurzokov, 1972).

Lominadze et al. (1971) estimated the efficiency of the anti-hail work over agricultural regions in Georgia during 1969. Personnel of the Transcaucasian Scientific Research Hydrometeorological Institute seeded clouds over an area of about 170,000 hectares. They claimed that their techniques are reliable and economically feasible and employ smaller quantities of toxic reagents than other hail suppression techniques.

In a newspaper article (TASS, 1971) a report was given of hail suppression work being conducted in the Fergana Valley near Tashkent. During the year, over an area of 243,000 hectares, 50 clouds were seeded with rockets and artillery shells. This was the third year that the Central Asiatic Regional Scientific Research Hydrometeorological Institute had been seeding potential hail clouds in the Fergana Valley.

Abdumalikov et al. (1969) discussed hailstorm seeding activities in Central Asia, particularly the Gissav Valley in Tadzhik SSR, during the period 1964 to 1968. This is an area of cotton farming.

Although the statistical data suggest seeding reduced hail damage, the authors cautiously stated, "It can ... be assumed that some success in reducing hail damage was attained". They also wrote that sometimes the experiments "had negative results; hail damage was observed when correct seeding procedures were followed in modifying clouds by means of small rockets (PGI-M), and also when using the "El'brus-2" shells". On one day seeded clouds produced hail as large as 4-cm in diameter. This is by far the most reserved statement on the efficacy of hailstorm seeding found so far in the Soviet literature.

8. Summary Comments

This latest review of Soviet research on weather modification contains few new developments. The major investment in weather modification activities in the USSR is still in the area of hail suppression. The report by Abdumalikov et al. (1969) is regarded as somewhat surprising and possibly quite significant. It is the first published article found to date indicating that the rocket and artillery seeding techniques sometimes fail. It strikes a cautious tone about the effectiveness of the Soviet hail suppression techniques, and to this extent differs significantly from the large number of other reports which regard the hail suppression problem as being solved. Some effort is being devoted to the study of the dissipation of warm fog and clouds, but they still seem to be fairly modest. A

few scientists have examined the effects of ice-nuclei seeding on the electrical properties of clouds and lightning, again the effort is small.

On the basis of data collected during a hail suppression program in Moldavia, a study was made of rainfall at the ground. It was concluded that the seeding increased the precipitation. Scientists in the Ukraine have tested the ideas of a convective cloud seeding advanced by Joanne Simpson and her associates. Presumably they were inspired by Dr. Simpson's detailed discussion of her research during her visit to the USSR in 1969.

At the All-Union Conference held in Tblisi in 1969, Dr. E. K. Fedorov, Director of the Main Hydrometeorological Service, called on Soviet scientists to carry out weather modification programs over large weather systems. There is no evidence in the literature covered in this review that his admonition was heeded.

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